INVESTIGATIONS

INTO

BLAST AFFECTED MARBLE

AT THE

PENRICE QUARRY

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Submitted in fulfilment of the requirements for the degree of Master of Economic Geology

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Penrice Quarry, Angaston

PREFACE

To the best of my knowledge this thesis contains no material which has been accepted for the award of any other higher degree or graduate diploma in any tertiary institution. It is also my belief that this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

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ABSTRACT

The Penrice Quarry in South Australia mines chemically pure marble for use in the chemical industry. The Quarry's major customer is the Penrice Soda Products plant at Osborne, S.A., where 508,000 tonnes of high grade marble are used per annum. The marble is burnt in vertical shaft kilns (calcining) as part of the Solvay Process for soda ash (sodium carbonate) manufacture.

Since early 1993 the kilns operations have been plagued by elevated kiln pressures coupled with the production of undesirable wastes called 'grits' (i.e. fine grained, partly calcined marble). These undesirable operating parameters and end products create limitations within the kilns plant and ultimately affect the down stream production of soda ash.

It is known that the Penrice marble, although chemically pure, does not always behave ideally during calcining as it often has a tendency to disintegrate in the kilns. This disintegration, termed 'decrepitation', generates excessive amounts of granular material that interferes with the airflow updraft in the kilns. This results in elevated kiln pressures, increases in 'grits' production and difficulties in controlling other operating parameters. Given these criteria, it was apparent that this decrepitation had been the major contributor to these poor kilns performances since early 1993.

Consequently, it was decided that a series of new investigations needed to be undertaken to determine:

i. The major cause(s) at the quarry of potentially decrepitating marble given that the kilns operations are essentially constant,

ii. Why the levels of decrepitation have increased, and

iii What changes could be made to current quarry practices to prevent or at least minimise the occurrence of decrepitating marble.

These investigations commenced with a break down of the current mining practices at the quarry which indicated that the most significant change to occur was the introduction of new production scheduling procedures (i.e. in-pit blending). Production records showed that since the introduction of these new scheduling procedures a significant proportion of marble for the Osborne plant was sourced from the lower benches in the northern end of the pit. Historically this marble was considered to be of unsuitable grade for the Osborne plant and as such almost all Osborne marble was sourced from the southern end of the pit.

Further investigations indicated that the major difference between the southern and northern ends of the pit was that much of the mining in the northern end of the pit was below the water table and necessitated the use of waterproof explosives (i.e. Handibulk Wet*).

For this reason it was decided to engage ICI Explosives to undertake some trial blasts and subsequent photogrammetric analyses to determine the differences between wet and dry blasts and the influence

they had on the production of potentially decrepitating marble. The trials showed that both wet and dry hole blasts produced structurally weak marble around the explosive column in the blastholes, which was subsequently termed 'blast affected marble'. The main finding of the blasting trials was that wet hole blasting (Handibulk Wet) produced 6.6 per cent blast affected marble while dry hole blasting (ANFO) produced only 1.5 per cent. These results suggested that the increase in decrepitation and therefore poor kiln performances were linked to an increase in the utilisation of low strength (i.e. blast affected) marble as a result of increased wet hole blasting.

Petrographic analyses were undertaken by the author in an effort to understand the nature and intensity of the fracture systems produced via blasting and how those findings could be related to blasting practices. Some point load strength tests were also conducted in order to gain an appreciation of the degree of strength loss produced between heavily blast affected marble and marble unaffected by blasting.

Blend changes incorporating less marble from the northern end of the pit have helped to alleviate the problem while further work is continuing into alternative explosive types and dewatering methods within the lower benches of the pit to enable ANFO type explosives to be used.

ACKNOWLEDGEMENTS

The author wishes to thank Penrice Soda Products Pty. Ltd. for allowing the opportunity to undertake these studies. Thanks also goes to the many Penrice people who offered technical advice and entered into the many lively discussions pertaining to this thesis.

Particular thanks goes to ICI Explosives Technical Services for agreeing to undertake the trial blasts and enabling the author to access all the technical data as well as engineering support.

Finally thanks goes to the CODES Key Centre for providing an industry relevant course with excellent content and support facilities.

CONTENTS

1. INTRODUCTION

The Penrice marble quarry is situated 2.5 kilometres northwest of the town of Angaston, on Sections 1738, 302, 1740 and 349, also Lot 1 of the Hundred of Moorooroo, County Light, South Australia (Figure 1 - Location of the Penrice Quarry).

The mining tenement of the quarry comprises two private mines: PM120 is owned by Penrice Soda Products Pty. Ltd. and PM86 is owned by the District Council of Angaston and leased by Penrice Soda Products Pty. Ltd. Both private mines are worked by Penrice Soda Products Pty. Ltd. as a single mining operation. Average production from the mine is approximately 1,500,000 tonnes per annum with an additional 600,000 tonnes of waste also being removed.

The prime purpose of the quarry is to supply consistent, high quality calcium carbonate for use in the Penrice Soda Products soda ash plant at Osborne, South Australia. The quarry produces 508,000 tonnes per annum of plus 50 mm to minus 150 mm size stone for this purpose.

Operational problems at the Osborne plant, in particular the kilns operation, have prompted investigations into the effects of blasting on the mechanical strength of the marble. Blast affected marble is the single greatest contributor to 'decrepitation' - the tendency of low strength marble to disintegrate within the kilns thereby generating excessive granular material that interferes with airflow in the kilns and facilitates the production of undesirable waste products and poor operating conditions. Costs to the kilns operation are in the order of $500,000 per annum.

Blast affected marble consists, broadly, of two components (pers. comm. R. Bluck):

1. White, opaque marble with strong penetrative cleavages and slickensided fractures (chalk zone), and

2. White, opaque marble with recognisable crystal structure and rare to weak penetrative structures (transition zone).

New investigations undertaken by ICI Explosives and the Penrice Quarry have indicated that blast affected marble is produced by blasting in both wet and dry ground conditions but to varying degrees depending on the Velocity of Detonation (VOD) of the explosive type being used. The two explosive types currently used at the Penrice Quarry are:

1. ANFO (Ammonium Nitrate and Fuel Oil), which is used exclusively for dry ground conditions because of it's tendency to desensitize in the presence of water. ANFO has a Velocity of Detonation around 3.5 kilometres per second and produces, on average, around 1.5 % blast affected marble, and

2. Handibulk Wet*, which is used for wet ground conditions, has a Velocity of Detonation (VOD) around 5.1 kilometres per second and produces, on average, around 6.5 % blast affected marble. The Fragmentation Energy of Handibulk Wet, that is, the fragmentation capacity of the explosive relative to ANFO is 159 per cent.

In addition, petrographic investigations were conducted on both a mesoscopic and a microscopic scale and these showed that two fracture systems dominated, namely intragranular and intergranular. This work was considered to be beneficial as no petrographic work of this nature had been undertaken previously and as a result there was no specific information on fracture system characteristics. Some point load strength tests were also conducted on hand specimens ranging from intensely blast affected marble to marble unaffected by blasting. These tests were conducted to gain an appreciation of the loss in mechanical strength that had occurred as a result of blasting.

There were a number of limitations to this study, which include:

i. The Penrice quarry is the only high grade marble deposit of it's type in Australia which has made comparisons with similar deposit types very difficult.

ii. Penrice Soda Products is Australia's sole soda ash producer which has made it impossible to make comparisons on marble behaviour in vertical shaft kiln operations elsewhere.

iii. The marble provided to the soda ash plant is of a specific size range and as such requires controlled fragmentation to obtain the maximum yield of marble in this range. This is unlike most quarry operations which are mainly concerned with achieving good fragmentation. There is no documented evidence that the 'decrepitation' phenomena, experienced with the Penrice marble, has been of any interest to any other quarrying operation. This has meant that very little study or investigation has been undertaken to understand this aspect of fragmentation / blast damage.

iv. Trial blasts are expensive and time consuming and involve the input of technical services from the explosive supplier, in this case, ICI Explosives. Coordination of these has been extremely difficult and has proven to be a drain on the resources of ICI Explosives in particular.

* Handibulk Wet is a registered trademark of ICI Explosives.

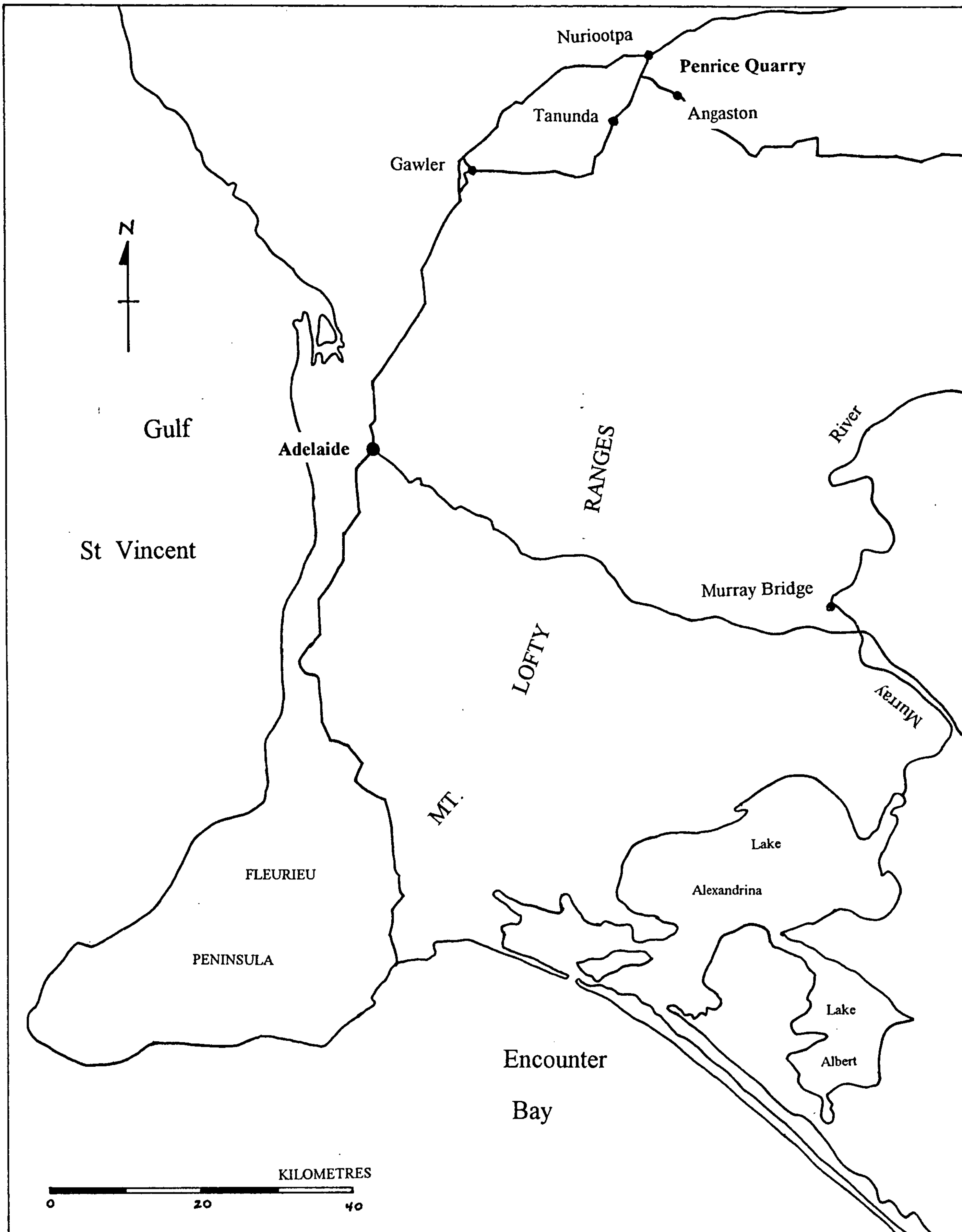

Figure 1: Location of the Penrice Quarry, South Australia.

2. GEOLOGICAL SETTING

The Penrice area lies within the eastern Mount Lofty Ranges (Stansbury Basin) and comprises a sequence of Cambrian metasediments and volcanics (Normanville and Kanmantoo Groups).

The Penrice Quarry is situated in the Angaston Marble unit (Normanville Group) which represents part of an Early Cambrian marine transgression where carbonate-dominated sediments were deposited in the Stansbury Basin after a hiatus in sedimentation in the Adelaide Geosyncline at the end of the Neoproterozoic.

In the Adelaide Geosyncline, mostly greenschist facies metamorphism and compressional deformation of the Cambro-Ordovician Delamerian Orogeny commenced in the Fleurieu Arc, with northwest-directed thrusts and folds and cleavage development (Drexel *et* al, 1995). However, in the eastern Mount Lofty Ranges (includes the Penrice area) the early structures were refolded by more upright, approximately meridional folds accompanied by amphibolite metamorphism (Drexel *et* al, 1995). The Penrice Quarry is situated on the eastern limb of an upright, moderately tight, southerly plunging (approximately 40^0) anticline with a north-south trending axial surface. The amphibolite-facies rocks of the eastern Mount Lofty Ranges (includes Penrice area) are characterised by strong schistosity sub-parallel to bedding.

Metamorphic zoning of the geosyncline as outlined by Drexel *et al*, 1995 (Figure 2 - Delamerian structural and metamorphic map of the Mount Lofty Ranges) places the Penrice Quarry largely within the prismatic sillimanite zone with the andalusite-staurolite zone occurring on the eastern margin of the deposit.

During the latter stages of the Cambro-Ordovician Delamerian Orogeny, dolerites, amphibolites and lamprophyres (including those of a kimberlite nature) intruded the Penrice area. Recent mapping in the Penrice Quarry also noted amphibolite dykes, folded with the Angaston Marble (Normanville Group) which are geochemically similar to the Late Cambrian, Suite 2 rocks described by Rankin *et al.* (1991b).

Uplift of the Adelaide Fold Belt (i.e. that part of the Adelaide Geosyncline affected by the Cambro-Ordovician Delamerian Orogeny) occurred during the late Tertiary resulting in large scale block faulting. Faulting within the Penrice area is dominated by a large scale north-south trending normal fault (called the Stockwell Fault) which truncates the western limb of the anticlinal fold on which the Penrice Quarry is situated.

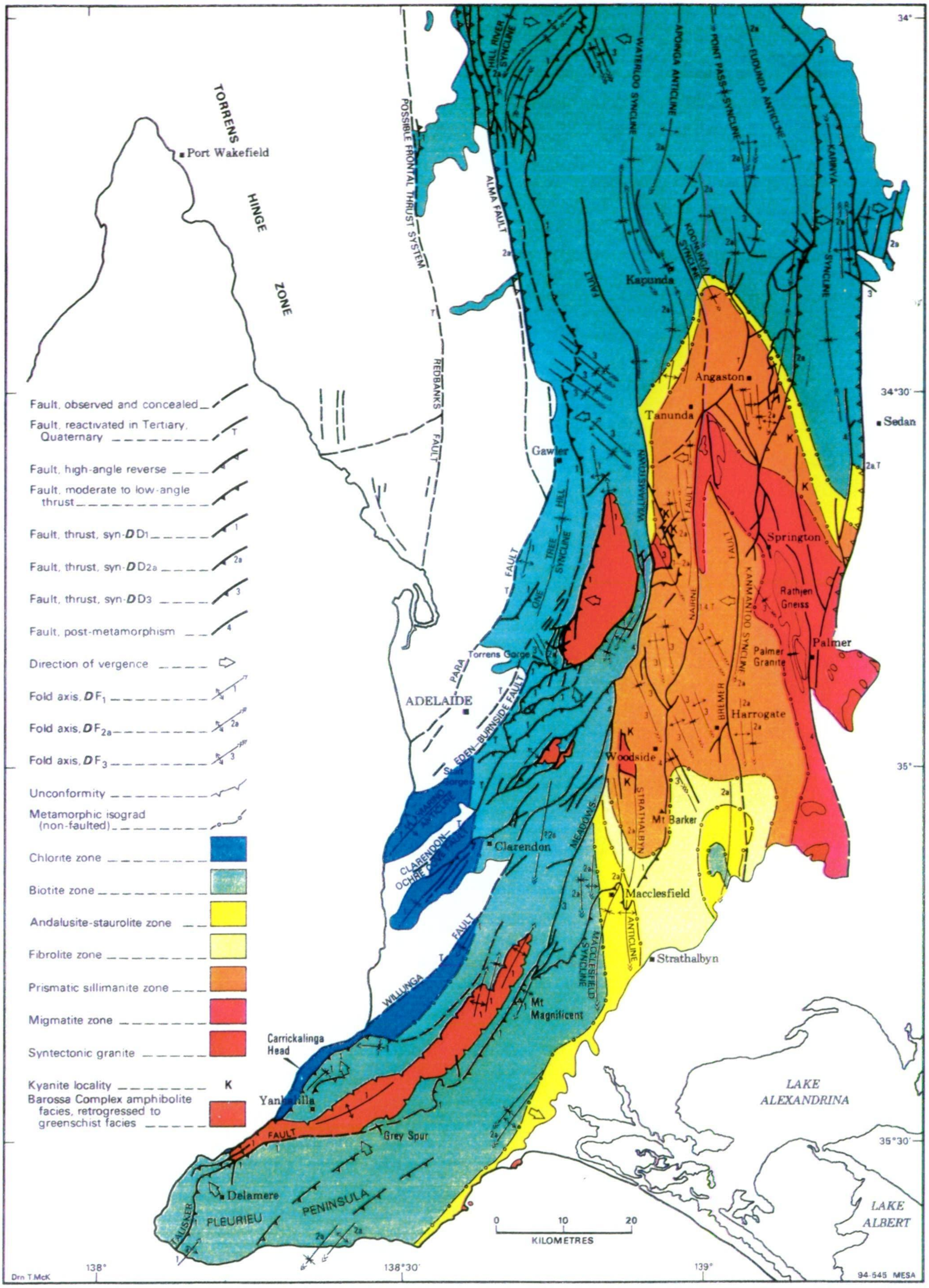

Figure 2: Delamerian structural and metamorphic map of the Mount Lofty Ranges (Bulletin 54).

3. PENRICE MARBLE

The Penrice marble is comprised largely of white to light grey, medium to coarse grained, saccharoidal marble with rare to minor disseminations of fine grained silicates (i.e. biotite, muscovite, garnets and scapolite series minerals), sulphides (i.e. pyrite, chalcopyrite, bornite and pyrrhotite) and oxides (i.e. hematite, magnetite and goethite). Grains range from equant to lath-like with irregular, sutured grain boundaries dominating. Where lath-like grains are dominant a distinct mineral lineation is often observable within the marble.

A typical chemical analysis for the Penrice marble is listed below:

Calcium carbonate	$CaCO_3$	96.50 %
Magnesium carbonate	$MgCO_3$	1.50 %
Silica	SiO_2	1.20 %
Iron oxide	Fe_2O_3	0.50 %
Aluminium oxide	Al_2O_3	0.30 %

The marble is well jointed with joints exhibiting rough, irregular surfaces on a mesoscopic scale and curved, wavy surfaces on a macroscopic scale. The joints are generally open to some extent with apertures ranging from microscopic to approximately 5 mm. The majority of the joints are discontinuous and many are en-echelon suggesting that most have been formed by extension. In some areas joints have been partly recemented by calcite presumably derived from solution of the marble at higher levels. In these areas the strength of the recemented joint is comparable to the marble strength.

Point load testing that was conducted on numerous hand specimens from the various sample locations within the pit indicated that the Penrice marble had a mean Point Load Strength Index of 8.0 MPa. This testing places the Penrice marble in the very high strength range with an inferred mean unconfined compressive strength in the order of 150 MPa (Figure 3 - Rock substance strength terms).

Rock Strength Class (1)	Abbreviation	Point Load Strength Index (MPa)	Approximate Unconfined Compressive Strength (MPa)
EXTREMELY LOW	EL		
		0.03	0.7
VERY LOW	VL		
		0.1	2.4
LOW	L		
		0.3	7
MEDIUM	M		
		1	24
HIGH	H		
		3	70
VERY HIGH	VH		
		10	240
EXTREMELY HIGH	EH		

(1) As defined in Broch, E. & Franklin, J. A., 1972. "The Point Load Strength Test". Int. J. Rock. Mech. Min. Sci., Vol. 9, pp. 669-697.

Figure 3: Rock substance strength terms.

4. TECHNICAL INVESTIGATIONS

Technical investigations into the blast affected marble occurred in two stages:

Stage One - involved the set-up, initiation and measurement of two adjacent trial blasts, on the eastern wall, in the northern end of the pit. One blast was conducted under dry ground conditions using ANFO while the other was conducted under wet ground conditions using Handibulk Wet. Photographic analyses of the blasted rock piles were conducted by ICI Explosives - Technical Services with subsequent interpretation of the data. The Technical Services group at the quarry was responsible for blast preparation (i.e. drilling, loading, hooking up and firing) as well as the provision of all information pertinent to the interpretation of the results.

Stage Two - involved petrographic analyses (both mesoscopic and microscopic) as well as some point load tests of a range of variably blast affected marble samples (i.e. marginally to intensely blast affected). This stage was aimed at gaining a greater understanding of the way in which the explosives altered the structural / mechanical characteristics of the marble and if any recommendations on controlling or alleviating the problem could be made.

4.1 STAGE ONE - TRIAL BLASTING

The Penrice Quarry enlisted the expertise of ICI Explosives - Technical Services to conduct two trial blasts aimed at quantifying the levels of blast affected marble attributable to both wet hole blasting (Handibulk Wet) and dry hole blasting (ANFO). The blasting trials were conducted on the eastern wall in the northern end of the pit, in an area where the geology was such that side by side blasts could be compared under the assumption of constant geology. The blasts were also conducted in an area where groundwater is present so the holes for the ANFO blast were fully dewatered prior to loading and then fired immediately so that no water ingress into the holes could occur.

The blasting geometry that was used in the trials was as follows:

Blast size:	3,500 tonnes
Number of rows:	2
Holes per row:	5
Pattern type:	staggered

Hole diameter:	114 mm
Hole angle:	10^0 - 15^0
Bench height:	12 metres
Subdrill:	1.5 metres
Burden:	3.6 metres
Spacing:	3.6 metres

ICI Explosives designed the blasts at 10 holes (i.e. approximately 3,500 tonnes) because, according to Browne (1994), it allowed them to undertake reasonably intense monitoring over a manageable total tonnage.

In order to gain maximum understanding of the trial results Penrice requested that the geometry of the blasts be surveyed prior to blasting. ICI Quarry Services were employed to undertake both Face Profiling and Boretrak (TM) services for the measurement of face geometry and front row hole alignment (Figure 4: Blast hole survey results). Appendix 1 contains the blasthole survey reports as produced by ICI Quarry Services.

Fragmentation analyses were conducted by ICI Explosives on the blasted rock piles using a photographic / digitisation technique. The photographs were taken regularly throughout the digging of the blasts and were spaced at 5 - 10 metre centres on each complete pass of the rock pile by the front end loader. A 2.08 metre by 2.08 metre scaling frame was used in each photograph.

Blast affected rocks were marked within the blasts using fluorescent paint in order to enable them to be easily identified in the photographs for separate digitisation. From this digitisation the volume of blast affected rocks as a percentage of the total rock mass could be determined. ICI Explosives Technical Services stated that this method enabled them to only measure rock particles in the + 0.1 metre size range. This was considered acceptable as much of the rock less than 0.1 metres in size would have been comminuted to less than 0.05 metres (i.e. lower size limit of the kiln raw feed) in the crushing and screening process.

ICI Explosives also used a Powerline (TM) unit to record continuous Velocity of Detonation (VOD) measurements. This is a good quality control measure as explosive VOD is a good indicator of whether an explosive is performing to specification. In this situation it is particularly important in providing insight into any potential for desensitisation of the explosive.

It should be noted that the initiation sequences used for the trial blasts were identical and representative of current blasting practices at the Penrice Quarry. Both blasts used 17 millisecond delays between holes and 65 millisecond delays between rows. Although the blasting trials contained no direct comparison of initiation sequence with levels of blast affected marble, it is known from both trial and error over many years and a long association with ICI Quarry Services that 65 millisecond burden delays allow an optimum configuration for burden relief and rock pile throw. This initiation sequence has also been modelled on ICI Explosives Shotplan (TM) software which has confirmed the in pit observations. ICI Explosives Technical Services also suggested that these initiation characteristics may prove desirable in the reduction of blast affected marble.

The charge weights are determined as a function of blasthole spacing, row burden, bench height and powder factor. The charge weights used were based on current blasting practices which have been developed with the aid of laser profiling and boretracking surveys over a number of years. The Penrice quarry has invested significant resources into determining the optimum charge weights for its operation because of the environmental sensitive area in which it is located (i.e. closest quarrying operation to housing in South Australia). The charge weights have also been designed to give optimum fragmentation (i.e. minimal fines and oversize) without prohibitively high explosive costs.

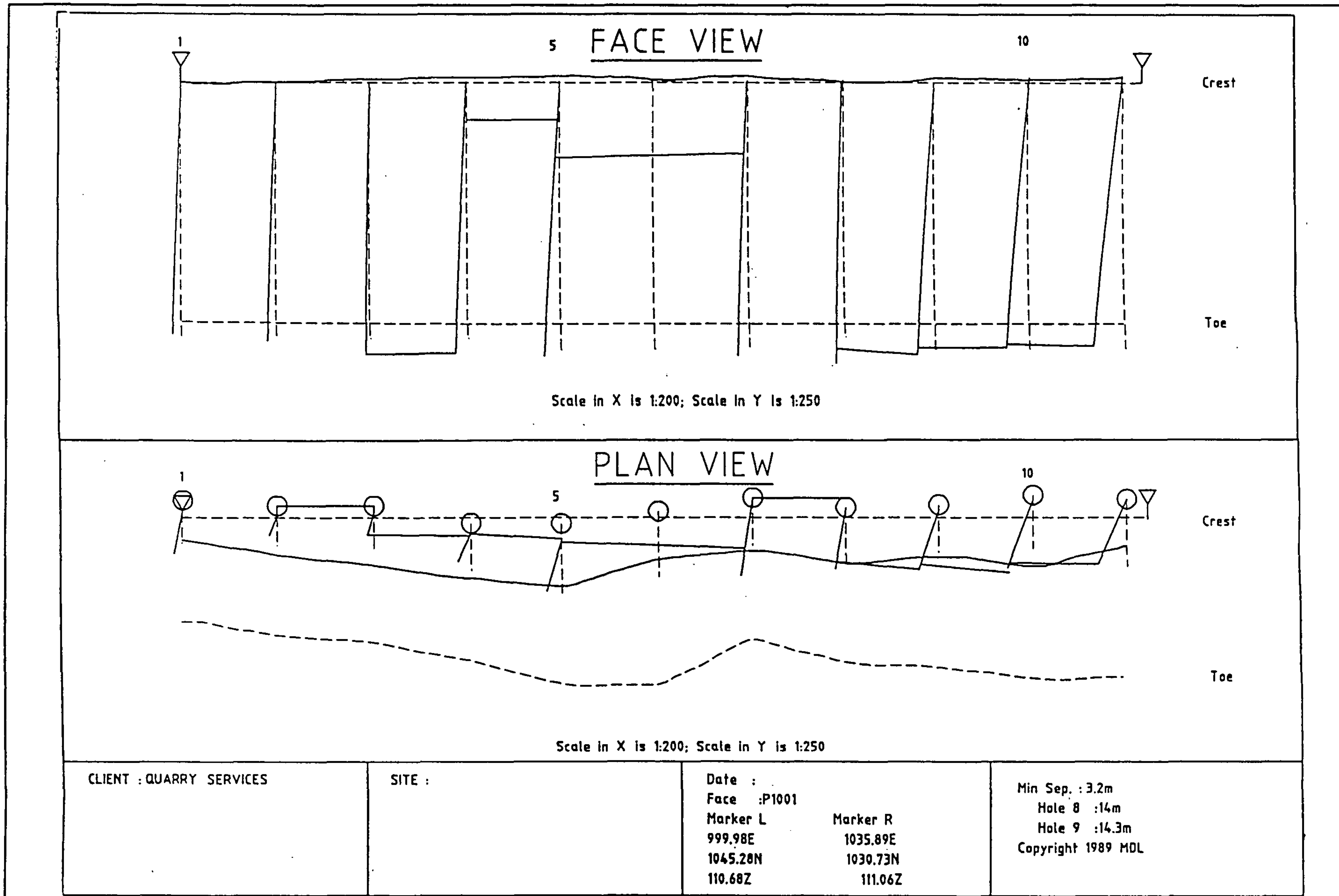

Figure 4: Blast hole survey results (From ICI Quarry Services)

4.1.1 WET HOLE BLAST - HANDIBULK WET

The nine blastholes for the wet hole trial blast (Handibulk Wet), were deck loaded[1] according to standard blasting practices at the Penrice Quarry. The details of each hole are outlined in Table 1.

Hole No.	Hole Depth (m)	Bottom Deck Length (m)	Deck Stemming Length (m)	Top Deck Length (m)	Stemming Length (m)
A1	13.1	4.7	2.1	1.9	4.4
A2	13.3	4.7	2.3	1.9	4.4
A3	14.1	5.4	2.5	1.9	4.3
A4	13.8	5.4	2.5	1.9	4.0
A5	14.3	5.7	2.4	2.2	4.0
B1	14.0	5.4	2.4	2.0	4.2
B2	13.7	5.5	2.1	1.9	4.2
B3	14.1	5.9	2.1	2.0	4.1
B4	13.6	5.3	2.4	1.9	4.0

Table 1 : Blasthole details for wet hole trial blast (after ICI Explosives).

The powder factor, that is, the ratio between the mass of the explosives required to break a given quantity of rock, was calculated at 0.57 kilograms per cubic metre.

The Powerline unit, used to record continuous Velocity of Detonation (VOD) measurements showed that the Handibulk Wet detonated with an average velocity of 5.1 kilometres per second. The results were further analysed by ICI Explosives who noted that the correlation coefficient for each of these measurements was very close to 1.0 indicating that the VOD was steady state in each application.

A fragmentation analysis was conducted by ICI Explosives on the blasted rock pile according to the field technique outlined in Section 4.1. These measurements were undertaken by ICI Explosives personnel under the supervision of the Penrice Quarry Technical Group. The summary of the fragmentation analysis for the Handibulk Wet blast is outlined in Table 2.

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[1] deck loading - is a technique of dividing the explosive column into two or more charges in the same blast hole. Reasons for doing this are to ensure better energy distribution and to minimise environmental impacts (i.e. ground vibration).

% PASSING	SIZE (m)
50%	0.27 m
80%	0.60 m
95%	1.09 m

Size (m)	% Passing
0.1	33.51
0.2	42.79
0.3	53.55
0.4	64.26
0.5	72.69
0.6	79.76
0.7	84.90
0.8	88.98
0.9	91.95
1.0	93.47
1.1	95.63
1.2	96.74
1.3	97.34
1.4	97.75
1.5	98.22
1.6	98.56
1.7	98.67
1.8	99.07
1.9	99.54
2.0	99.54
2.1	99.54
2.2	99.54
2.3	99.54
2.4	100.00

Total Area (m^2) = 302 m^2

Number of rocks = 4,468

Characteristic size = 0.381 m

Uniformity Index, n = 1.04

Table 2: Results of fragmentation analysis for wet hole trial blast (after ICI Explosives).

The raw data from the fragmentation analysis were used to determine the level of blast affected marble within each size range. Table 3 shows the level of blast affected marble represented as a percentage of the total rock volume for each size interval.

Size (m)	% of Total Rock Volume	Total Area Measured by Fragmentation Analysis (m^2)	Measured Area of Blast Affected Marble (m^2)	Blast Affected Marble as a % of Rock Volume at each Size Interval
0.1	33.51	103.00	N.A.	N.A.
0.2	9.28	28.56	1.93	6.75
0.3	10.76	33.13	1.86	5.60
0.4	10.71	32.97	2.11	6.40
0.5	8.43	25.94	1.77	6.83
0.6	7.07	21.75	1.26	5.81
0.7	5.14	15.82	0.77	4.84
0.8	4.07	12.58	0.86	6.82
0.9	2.97	9.13	0.76	8.32
1.0	1.53	4.69	0.28	5.92
1.1	2.16	6.65	1.04	15.68
1.2	1.11	3.43	0.48	13.86

Table 3: Levels of blast affected marble as a percentage of total rock volume (after ICI Explosives).

From Table 3 it can be seen that the level of blast affected marble, as represented as a percentage of total rock volume for each size interval, is reasonably constant except in the 1.1 metre and 1.2 metre size ranges where the percentage increases dramatically. This is an unexpected result as the low unconfined compressive strength of the blast affected marble generally limits its occurrence in the larger size fractions. However, the small total area measured for these two size fractions could allow relatively large percentage changes to occur for minor variation in the measured area of blast affected marble.

The measured volume of blast affected marble (+0.1 m) as a percentage of the total rock volume (+0.1 m) was 6.6 % for wet hole blasting (i.e. Handibulk Wet).

4.1.2 DRY HOLE BLAST - ANFO

The ten blastholes for the dry hole trial blast (ANFO) were, like the wet holes, deck loaded according to standard blasting practices at the Penrice Quarry. The details of each hole are outlined in Table 4.

Hole No.	Hole Depth (m)	Bottom Deck Length (m)	Deck Stemming Length (m)	Top Deck Length (m)	Stemming Length (m)
C1	14.4	5.9	2.3	2.6	3.6
C2	13.0	4.6	2.5	2.2	3.7
C3	14.3	5.8	2.7	2.1	3.7
C4	13.9	5.5	2.6	1.9	3.9
C5	14.0	5.7	2.5	2.1	3.7
D1	13.9	5.8	2.3	2.1	3.7
D2	13.9	5.5	2.7	2.0	3.7
D3	13.9	5.7	2.0	2.4	3.8
D4	14.1	5.6	2.5	2.2	3.8
D5	13.3	4.8	2.5	2.1	3.9

Table 4: Blasthole details for dry hole trial blast (after ICI Explosives).

The powder factor for the dry hole blast was calculated at 0.40 kilograms per cubic metre. As with the wet hole blast, ICI Explosives Technical Services used a Powerline unit to record continuous Velocity of Detonation (VOD) measurements for the dry hole blast. These measurements showed that the ANFO detonated with an average velocity of 3.7 kilometres per second. ICI Explosives noted that the correlation coefficient for each of these measurements was very close to 1.0 indicating that the VOD was steady state in each application.

A fragmentation analysis, identical to that for the wet hole blast, was conducted on the blasted rock pile from the dry hole blast (ANFO). The summary of fragmentation for the ANFO blast is outlined in Table 5.

% PASSING	SIZE (m)
50%	0.30 m
80%	0.59 m
95%	0.98 m

Size (m)	% Passing
0.1	33.21
0.2	42.45
0.3	53.71
0.4	63.76
0.5	72.60
0.6	80.40
0.7	86.47
0.8	90.56
0.9	92.98
1.0	95.71
1.1	96.56
1.2	97.76
1.3	98.57
1.4	99.35
1.5	99.79
1.6	99.79
1.7	99.79
1.8	100.00

Total Area (m^2) = 249 m^2
Number of rocks = 3,683
Characteristic size = 0.399 m
Uniformity Index, n = 1.218

Table 5: Results of fragmentation analysis for dry hole trial blast (after ICI Explosives).

Size (m)	% of Total Rock Volume	Total Area Measured by Fragmentation Analysis (m^2)	Measured Area of Blast Affected Marble (m^2)	Blast Affected Marble as a % of Rock Volume at each Size Interval
0.1	33.21	82.73	N.A.	N.A.
0.2	9.24	23.03	0.38	1.65
0.3	11.25	28.04	0.36	1.28
0.4	10.05	25.05	0.52	2.08
0.5	8.84	22.02	0.21	0.95
0.6	7.79	19.42	0.27	1.41
0.7	6.07	15.13	0.73	4.83
0.8	4.09	10.19	0.31	3.00
0.9	2.42	6.04	0.00	0.00
1.0	2.72	6.78	0.00	0.00
1.1	0.85	2.12	0.44	20.70

Table 6: Levels of blast affected marble as a percentage of total rock volume (after ICI Explosives).

Table 6 shows the level of blast affected marble represented as a percentage of the total rock volume for each size interval. From Table 6 it can be seen that the level of blast affected marble, as represented as a percentage of total rock volume for each size interval, is reasonably constant as with the wet hole blast. Similarly there is a dramatic increase in the percentage of blast affected marble for the 1.1 metre size range as compared to the other size intervals. This anomalous value may be the result of only a small number of 1.1 metre blast affected blocks given that the overall percentage of the blast contained in this size fraction is very small. Nevertheless, this anomalous result is an indication that the unconfined compressive strength of the blast affected marble is at times great enough to resist complete comminution to the finer size fractions prior to crushing and screening.

The measured volume of blast affected marble (+0.1 m) as a percentage of the total rock volume (+0.1 m) was 1.5 % for dry hole blasting (i.e. using ANFO).

4.1.3 ANALYSIS OF BLAST AFFECTED MARBLE MEASUREMENTS

i. RELATIVE BULK ENERGY (RBE)

Both the wet hole and dry hole trial blasts were drilled to the same geometry, being 3.6 metres (burden) by 3.6 metres (spacing). The powder factor comparison between the blasts will then, represent the Relative Bulk Energy (RBE) of each explosive product. The comparison of explosive RBE, powder factor and measured blast affected marble are outlined in Table 7.

CHARGE TYPE	RBE	POWDER FACTOR	BLAST AFFECTED MARBLE
HANDIBULK WET	159%	0.57 kg/m^3	6.60%
ANFO	100%	0.39 kg/m^3	1.50%
COMPARISON	159%	146%	440%

Table 7: A comparison between RBE, powder factor and blast affected marble for Handibulk Wet and ANFO (after ICI Explosives).

The above table indicates that although the level of blast affected marble increases with powder factor, the relationship between the parameters is not linear. This means that an increase in the level of blast affected marble is not caused solely from an increase in explosive energy level.

ii. VELOCITY OF DETONATION (VOD)

The Powerline unit used by ICI Explosives Technical Services provided a comprehensive record of Velocity of Detonation measurements for both trial blasts. It was believed that the level of blast affected marble was related to the shock energy component of the explosive charge and therefore greater levels of damage would be expected from emulsion type explosives (e.g. Handibulk Wet) compared to ANFO. This means that it could be approximated that higher VOD explosives will generate higher levels of blast affected marble. The comparisons of VOD and blast affected marble for the two trial blasts are outlined in Table 8.

CHARGE TYPE	VELOCITY OF DETONATION	LEVEL OF BLAST AFFECTED MARBLE
HANDIBULK WET	5.1 km/s	6.60%
ANFO	3.7 km/s	1.50%
COMPARISON	138%	440%

Table 8: A comparison of VOD versus blast affected marble (after ICI Explosives).

The results from Table 8 indicate that the level of blast affected marble increases with Velocity of Detonation, and as with the results from Table 7, the relationship is not linear. The results presented in both Tables 7 and 8 indicate that no one factor can be isolated as the cause of blast affected marble but, more likely, it is the result of a number of factors operating concurrently.

iii. FRAGMENTATION ANALYSIS

The resultant fragmentation distributions for Handibulk Wet and ANFO were very similar indicating that both explosive types performed a very similar amount of rock breaking work on the rock mass. A comparison of these distributions is outlined in Table 9:

% PASSING	HANDIBULK WET SIZE (m)	ANFO SIZE (m)
50%	0.27 m	0.30 m
80%	0.60 m	0.59 m
95%	1.09 m	0.98 m

Table 9: Comparison of fragmentation distributions for Handibulk Wet and ANFO (after ICI Explosives).

Despite the fact that both explosive types performed a very similar amount of rock breaking work the powder factors, strengths, shock characteristics and the levels of blast affected marble differed significantly between the two blasts.

4.2 STAGE TWO - PETROGRAPHIC INVESTIGATIONS

Stage two focused on gaining a greater understanding of the blast affected marble through a series of petrographic investigations at both a mesoscopic and a microscopic level. Of particular interest were the changes which occurred to the structure and therefore strength of the marble when it was acted upon by explosives (i.e. both Handibulk Wet and ANFO).

The petrographic investigations were carried out entirely by the author and represented a stream of petrographic work never before undertaken by Penrice.

Thirty samples, from various locations within the pit, were selected by the author for thin sectioning and petrographic analysis. However, not all of the samples have been presented in this study as a number of them exhibited similar properties enabling the sample list to be condensed. The samples were largely chosen from the major producing benches within the pit but were also chosen in such a way that they represented both the lateral and vertical variations that occur within the marble. The samples from the northern end of the pit were chosen from an area adjacent to the trial blasts in order to add continuity to the study. Appendix 2 contains a map of the pit depicting all the sample locations.

The samples that were collected ranged from those which appeared unaffected by blasting to those which were quite visibly blast affected. Many of the samples, particularly the most heavily blast affected ones, were quite friable and as such tended to disintegrate during thin section preparation. Consequently, many of the samples were impregnated with a blue dyed araldite prior to thin section preparation. This technique worked extremely well and enabled even the most heavily blast affected samples to be sectioned with minimal difficulty. The blue dye also enhanced visual detection of the fracture systems within many of the samples.

The petrographic investigations identified two major fracture types within the marble, namely, intergranular and intragranular fractures. The intergranular fractures, as would be expected, occur between the marble grains and indicate that the strengths of the individual grains is greater (in general terms) than the strength of the grain boundaries (i.e. cementing agent). The petrographic investigations tended to indicate that these intergranular fractures were more common in the finer grained samples or where grain boundaries were not well sutured.

The intragranular fractures, occur within the grains and tend to propagate across the grain boundaries without deviating in trend direction. These fractures tend to indicate that the strength of the individual grains is less than the strength of the grain boundaries. The petrographic investigations tended to indicate that these intragranular fractures were more common in the coarser grained samples and particularly where the grain boundaries were well sutured.

Where the marble has been heavily blast affected both intergranular and intragranular fractures often occur together, although one fracture usually dominates.

In addition to photomicroscopic investigations, some hand specimens of blast affected marble were point load tested to determine the Point Load Strength Index (PSLI) of the various samples. These values were then extrapolated to inferred mean unconfined compressive strengths (refer Figure 3). The various forms of blast affected marble were compared, in general terms, with the unaffected marble (i.e. not blast affected) from the same blast. In addition to these comparisons a count of fractures per centimetre was graphed against the Point Load Strength Index to gain an understanding of the effect of fracture density on rock strength. These results are discussed in section 4.2.3.

The hand specimens have been listed in ascending reduced levels (RL) with each sample set aimed at describing variously blast affected marble (i.e. unaffected to intensely blast affected) as is the case with the thin section samples.

4.2.1 HAND SPECIMEN DESCRIPTIONS

i. RL303, Eastern Wall, Northern Pit.

The marble from this area of the pit is a fresh, medium to coarse grained, white saccharoidal marble containing minor, fine grained sulphides (i.e. pyrite and chalcopyrite) and a variety of Ca-Al-Mg-Fe silicate minerals. These 'contaminants' usually occur as disseminations or rarely small pod/lenses.

Point load tests, on samples unaffected by blasting, range from 3.0 MPa to a high of 9.5 MPa which gives a Point Load Strength Index in the high to very high range.

303A: Fresh, medium grained marble, unaffected by blasting.

303B: Fresh, medium grained marble, partially affected by blasting.

Photomicrograph 1.

303C: Fresh, coarse grained marble, intensely blast affected. Hand specimen shows distinct slickensiding and some stretching of the sulphide grains.

Photomicrograph 2.

ii. RL315, Eastern Wall, Northern Pit.

The marble from this area of the pit is a fresh, medium grained, white saccharoidal marble containing minor sulphides (i.e. mainly pyrite and chalcopyrite) and a variety of Ca-Al-Mg-Fe silicates as fine grained disseminations.

315A: Fresh, medium grained marble, unaffected by blasting.

Photomicrograph 3.

315B: Fresh, medium grained marble, marginally affected by blasting.

Photomicrograph 4.

315C: Fresh, medium grained marble, moderately affected by blasting.

Photomicrograph 5.

315D: Fresh, medium grained marble, intensely affected by blasting.

Photomicrographs 6 and 7.

iii. RL348, Western Wall, Southern Pit.

The marble from this area of the pit is a fresh, medium to coarse coarse grained, white saccharoidal marble that contains minor fine grained Ca-Al and Fe-Mg silicate disseminations and minor inclusions of iron oxide (i.e. hematite, goethite and limonite). Point load tests, on samples unaffected by blasting, range from 8.0 MPa to 12.5 MPa with an average of 9.7 MPa, indicating a Point Load Strength Index in the very high range.

348A: Fresh, coarse grained marble, unaffected by blasting.

348B: Fresh, coarse grained marble, partially affected by blasting.

Photomicrograph 8.

348C: Fresh, medium grained marble, moderately affected by blasting.

348D: Fresh, coarse grained marble, heavily affected by blasting.

Photomicrograph 9.

v. RL360, Eastern Wall, Southern Pit.

The marble from this area of the pit is a fresh, fine to medium grained, white saccharoidal marble with rare to minor Ca-Al-Mg-Fe silicate disseminations and minor iron oxide staining along joint surfaces. Point load tests, on samples unaffected by blasting, average 8.0 MPa indicating that the marble is in the very high range of the Point Load Strength Index.

360A: Fresh, fine to medium grained marble, unaffected by blasting.

Photomicrograph 10.

360B: Fresh, fine to medium grained marble, partially affected by blasting.

Photomicrograph 11.

vi. RL372, Eastern Wall, Southern Pit.

The marble from this area of the pit is a fresh, medium to coarse grained, white saccharoidal marble with rare fine grained Ca-Al-Mg-Fe silicates (disseminated) and minor fine grained, iron sulphides. Slickensided surfaces are evident on the heavily blast affected marble with some stretching of the iron sulphide grains also occurring.

372A: Fresh, medium to coarse grained marble, unaffected by blasting.

372B: Fresh, medium to coarse grained marble, partially affected by blasting.

Photomicrograph 12.

372C: Fresh, medium to coarse grained marble, intensely affected by blasting.

Photomicrograph 13.

vii. RL384, Eastern Wall, Southern Pit.

The marble from this area of the pit is a fresh, fine to coarse grained, white saccharoidal marble with minor to moderate, very fine grained Ca-Al-Mg-Fe silicate disseminations and rare, very fine grained, iron sulphide disseminations. This area of the pit is characterised by a significant variation in the grain size of the marble over a relatively small lateral extent. Point load tests, on samples unaffected by blasting, average 8.0 MPa indicating that the marble is in the very high range of the Point Load Strength Index.

384A: Fresh, fine to medium grained marble, unaffected by blasting.

Photomicrograph 14.

384B: Fresh, coarse grained marble, partially affected by blasting.

384C: Fresh, coarse grained marble, heavily affected by blasting.

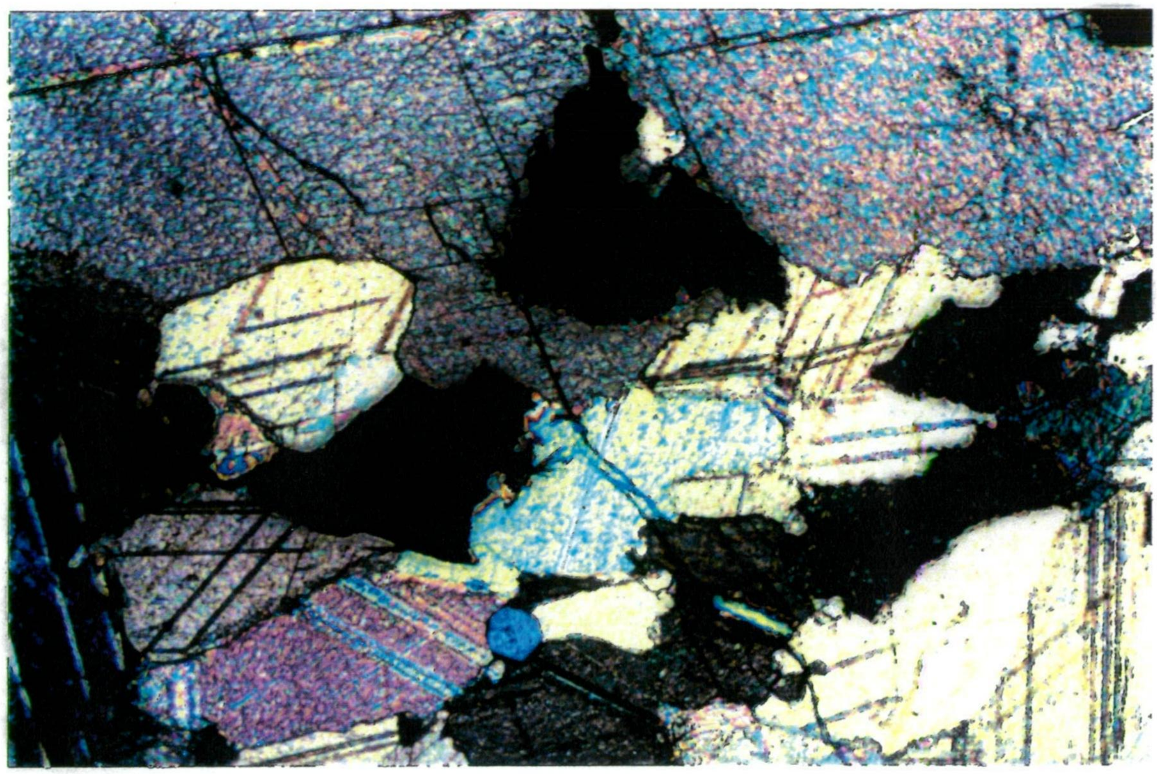
Photomicrograph 15.

4.2.2 THIN SECTION DESCRIPTIONS + PHOTOMICROSCOPY

i. RL303, Eastern Wall, Northern Pit.

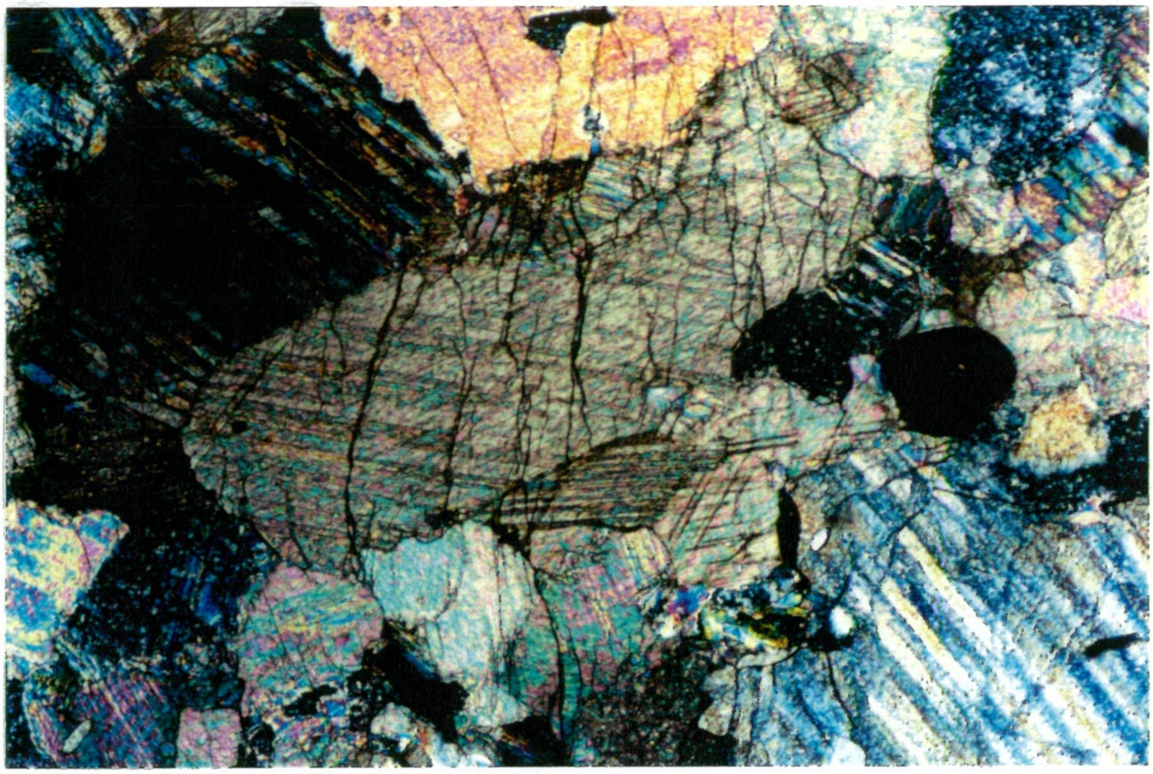
303A: Fresh, medium grained, white saccharoidal marble. Grains are up to 3 mm across. Irregular and sutured grain boundaries are common. Rare to absent intragranular and intergranular defects indicate minimal structural damage due to blasting.

303B: Fresh, medium to coarse grained, white saccharoidal marble with grains up to 4 mm across. Grain boundaries tend to be sutured and irregular. The sample exhibits a moderately distinct mineral lineation. Minor to moderate intragranular fracturing has occurred with the fractures propagating across grain boundaries without deviating. Some of these fractures tend to propagate in a step-like pattern and in the larger grains the fractures occur parallel to the long axis in the field of view (Photomicrograph 1). Blue dye, evident along some of the grain boundaries indicates that minor to rare intergranular fracturing has also occurred. This sample has been partially affected by blasting. Point load strength tests on this sample indicate a significant reduction in the Point Load Strength Index from approximately 8 MPa (unaffected by blasting) to 4 MPa or less.



Photomicrograph 1: Medium grained marble showing step-like propagation of the intragranular fracturing. Field of view 5 mm.

303D: Fresh, medium to coarse grained, white saccharoidal marble with grains up to 5 mm across. Grain boundaries where intact are sutured. Both intragranular and intergranular fracturing/dislocation have occurred as a result of blasting. Intragranular fracturing is intense and dominates the intergranular fracturing which is only moderate. This tends to indicate that the individual grain strength in this sample is low compared with the grain boundary strength. This is further supported by the fact that the fractures propagate through the grains without deviating at the grain boundaries (Photomicrograph 2). The Point Load Strength Index for this sample indicates that the rock strength class is low to medium at less than 1 MPa (i.e. can often be broken in hands).

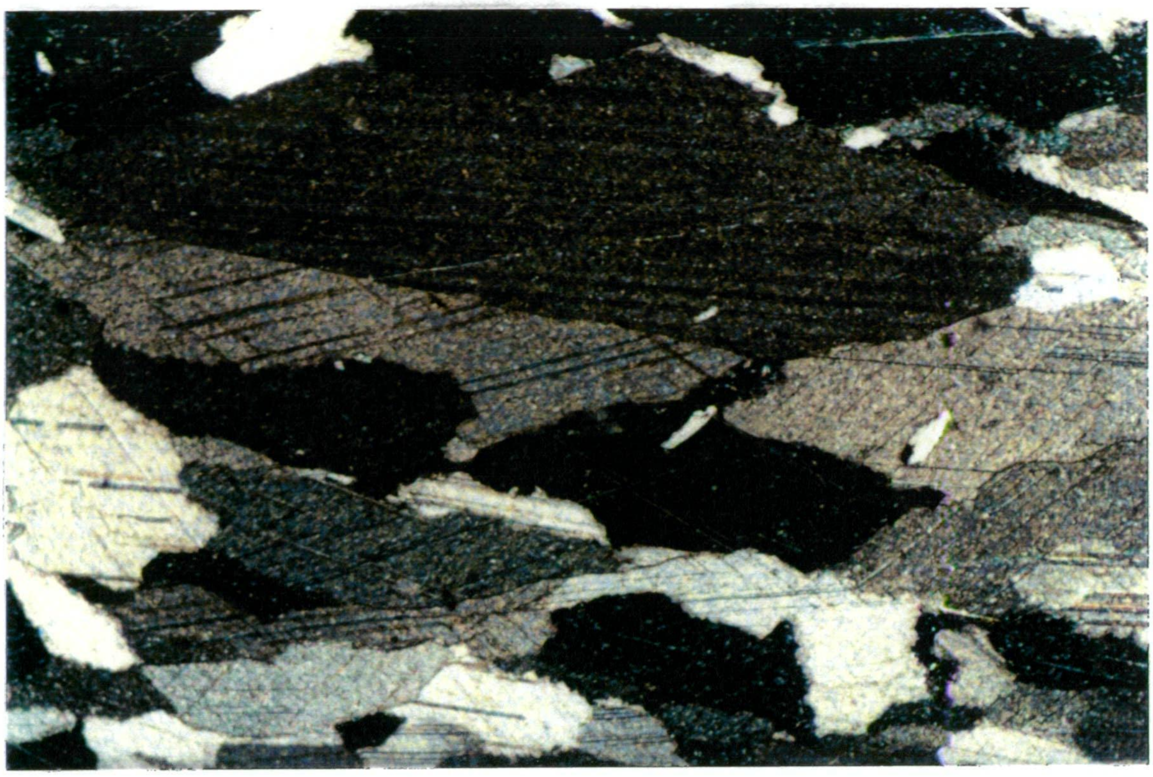


Photomicrograph 2: Coarse grained marble showing intense intragranular fracturing. Stepped and anastamosing fracture patterns are common. Field of view 5 mm.

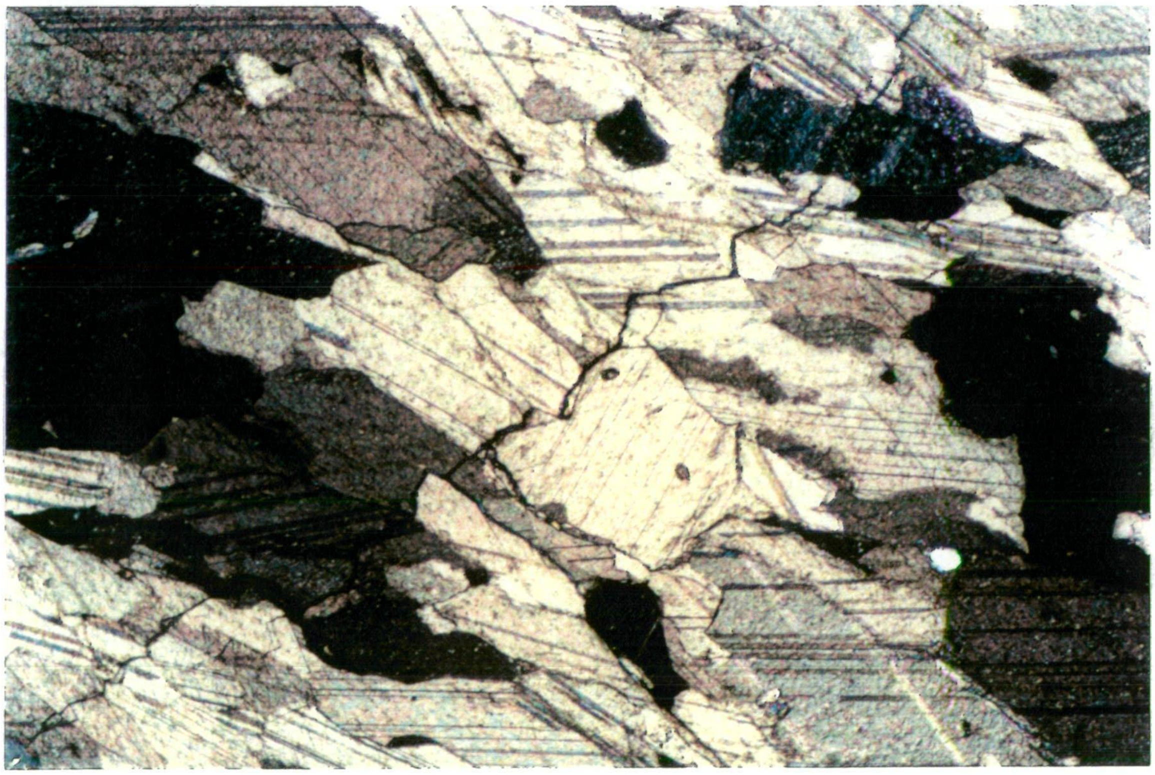
ii. RL315, Eastern Wall, Northern Pit.

315A: Fresh, medium to coarse grained, white saccharoidal marble with grains up to 5 mm in length. Grains show a distinct mineral lineation and tend to be elongate or lath-like rather than equant. Grain boundaries tend to be regular and sharp. No intragranular or intergranular fracturing has occurred indicating that this sample has been unaffected by blasting (Photomicrograph 3).

315B: Fresh, medium grained, white saccharoidal marble with grains up to 4 mm long. Grains tend to be elongate and exhibit a distinct mineral lineation. Minor intergranular and intergranular fracturing have occurred with no fracture type dominating (Photomicrograph 4). This sample has only been marginally affected by blasting. According to Bluck's broad classification (see Introduction) this sample would have been sourced from the 'transition zone'.

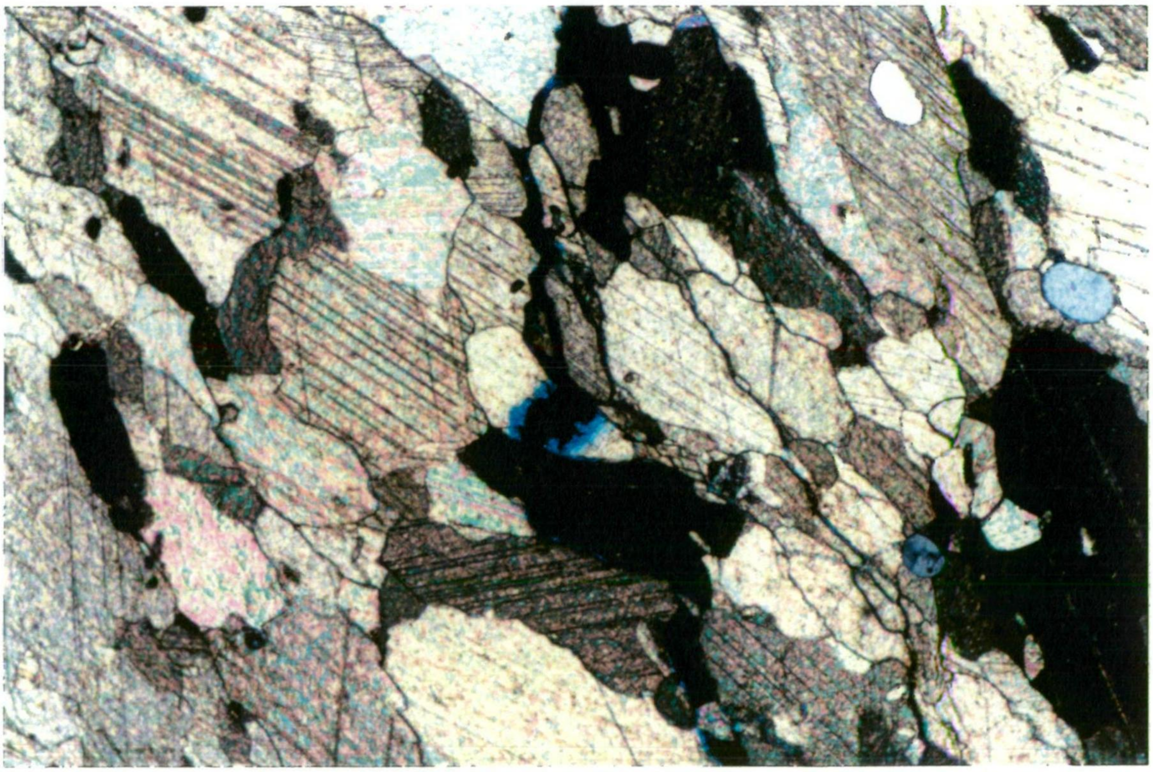


Photomicrograph 3: Fresh, medium grained marble unaffected by blasting. Field of view 5 mm.



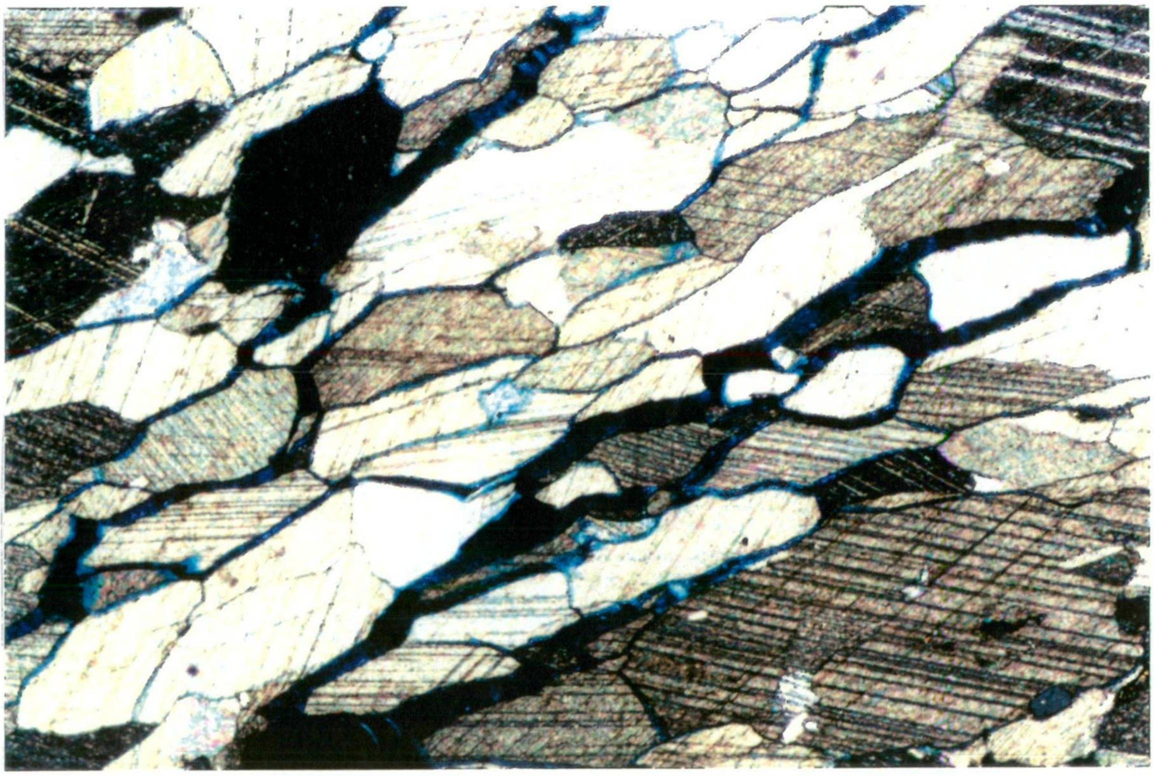
Photomicrograph 4: Fresh, medium grained marble with minor fracturing. Field of view 5 mm.

315C: Fresh, fine to medium grained, white saccharoidal marble with grains up to 4 mm long. Grains tend to be elongate or lath-like with largely regular grain boundaries. Intergranular fracturing is rare and intragranular fracturing tends to be minor. Where present the intragranular fractures are generally 'stepped' and they propagate across the grain boundaries without deviating along them (Photomicrograph 5). This indicates that the strength at the grain boundaries is slightly greater than that of the grains themselves. The Point Load Strength Index indicates a medium to high rock strength at between 1 and 3 MPa.

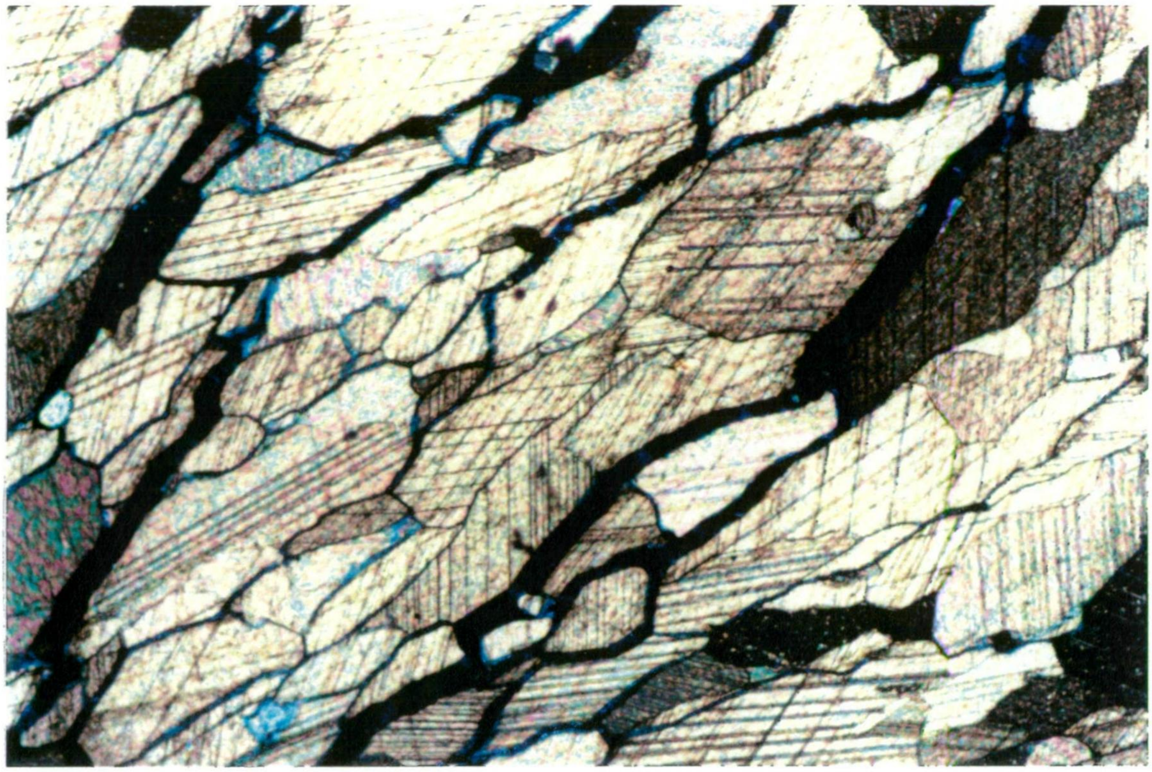


Photomicrograph 5: Fresh, fine to medium grained marble exhibiting moderate fracturing. Field of view 5 mm.

315D: Fresh, fine to medium grained, white saccharoidal marble with grains up to 3 mm long. The grains are generally lath-like to elongate and impart a distinct mineral lineation to the sample. The grain boundaries are generally sharp. Minor intragranular fracturing and moderate intergranular fracturing has occurred. This tends to indicate that, unlike sample 315C, the strength of the grain boundaries is slightly less than that of the grains themselves (Photomicrographs 6 and 7). This would be partly attributable to the finer grain size of this sample.



Photomicrograph 6: Fresh, medium grained marble exhibiting intense fracturing (depicted by blue dye). Field of view 5 mm.

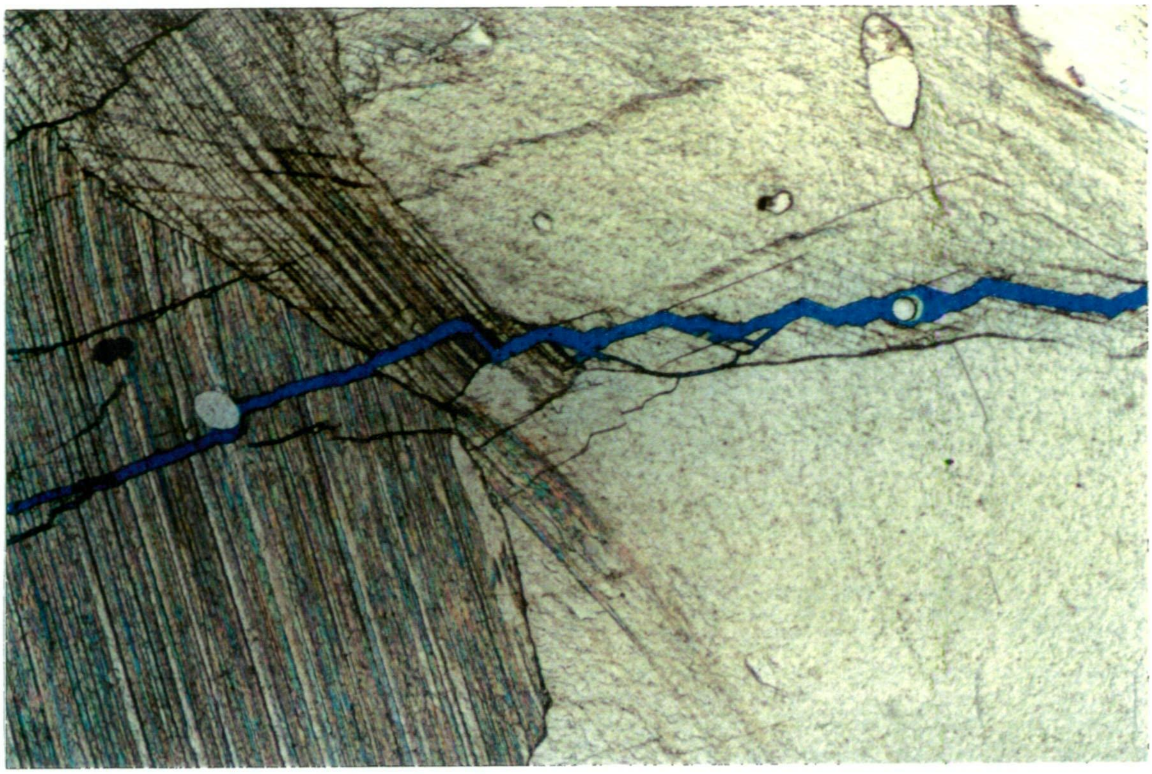


Photomicrograph 7: Fresh, medium grained marble exhibiting intense fracturing (depicted by blue dye). Field of view 5 mm.

iii. RL348, Western Wall, Southern Pit.

348A: Fresh, coarse grained, white saccharoidal marble with grains up to 6 mm long. The sample exhibits a distinct mineral lineation. Grains are generally lath-like with sutured grain boundaries. Intergranular and intragranular fracturing is rare to absent indicating that this sample has been unaffected by blasting.

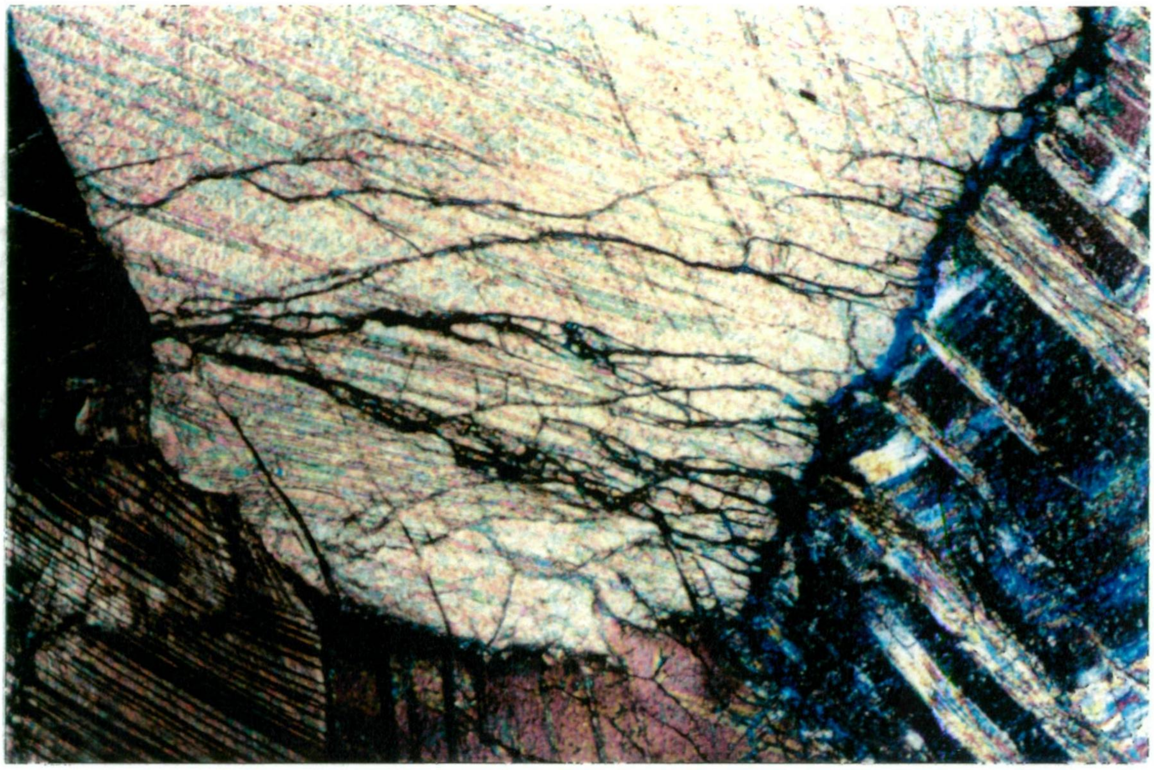
348B: Fresh, coarse grained, white saccharoidal marble with grains up to 7 mm long. Minor intragranular fracturing is evident within the larger grains and often exhibits an en-echelon fracture pattern (Photomicrograph 8). Intergranular fracturing is rare. There is no deviation of intragranular fractures along grain boundaries again indicating that the grain boundary strength is greater than the grain strength itself. The grain boundaries tend to be regular and sharp and are rarely sutured.



Photomicrograph 8: Fresh, coarse grained marble exhibiting intragranular fracturing (depicted by blue dye). Field of view 5 mm.

348C: Fresh, medium grained, white saccharoidal marble with grains up to 4 mm long. The grains range from equant to lath shaped with the sample exhibiting a reasonably distinct mineral lineation. The grain boundaries range from regular to irregular and sutured grain boundaries are quite common. Minor to moderate intergranular and intragranular fracturing has occurred throughout the sample with the intragranular fractures dominating. Some of the intragranular fractures terminate within the grain supporting the fact that this sample has only been moderately affected by blasting. The Point Load Strength Index indicates a medium rock strength at around 1-2 MPa.

348D: Fresh, coarse grained, white saccharoidal marble with grains up to 9 mm long. Grains tend to be lath-like and in places exhibit sutured grain boundaries. Intergranular fracturing is common but it is dominated by the intragranular fracturing which is often high density (Photomicrograph 9). The intragranular fractures often occur in an en-echelon pattern. In some of the grains an anastomosing fracture pattern also occurs. The dominance of the intragranular fractures over the intergranular fractures indicates that the grain strength is low in comparison to the grain boundary strength.

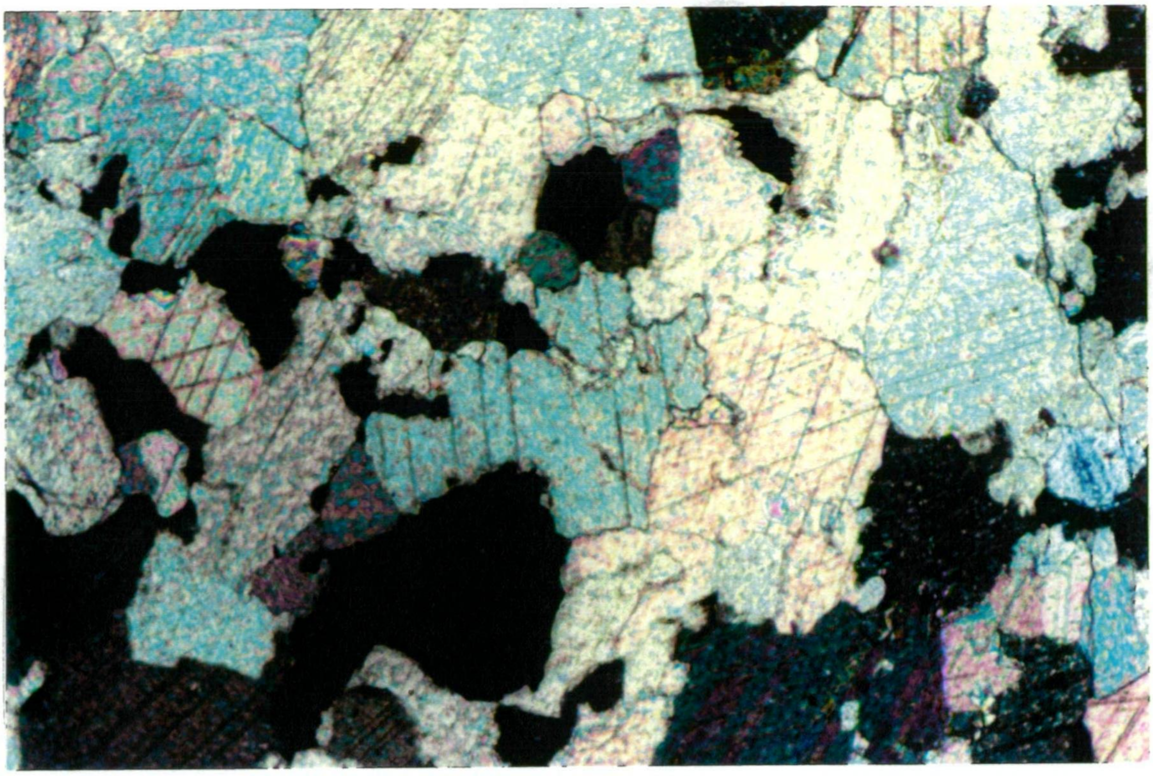


Photomicrograph 9: Fresh, coarse grained marble heavily affected by blasting. Intense, anastamosing intragranular fracture pattern is obvious. Field of view 5 mm.

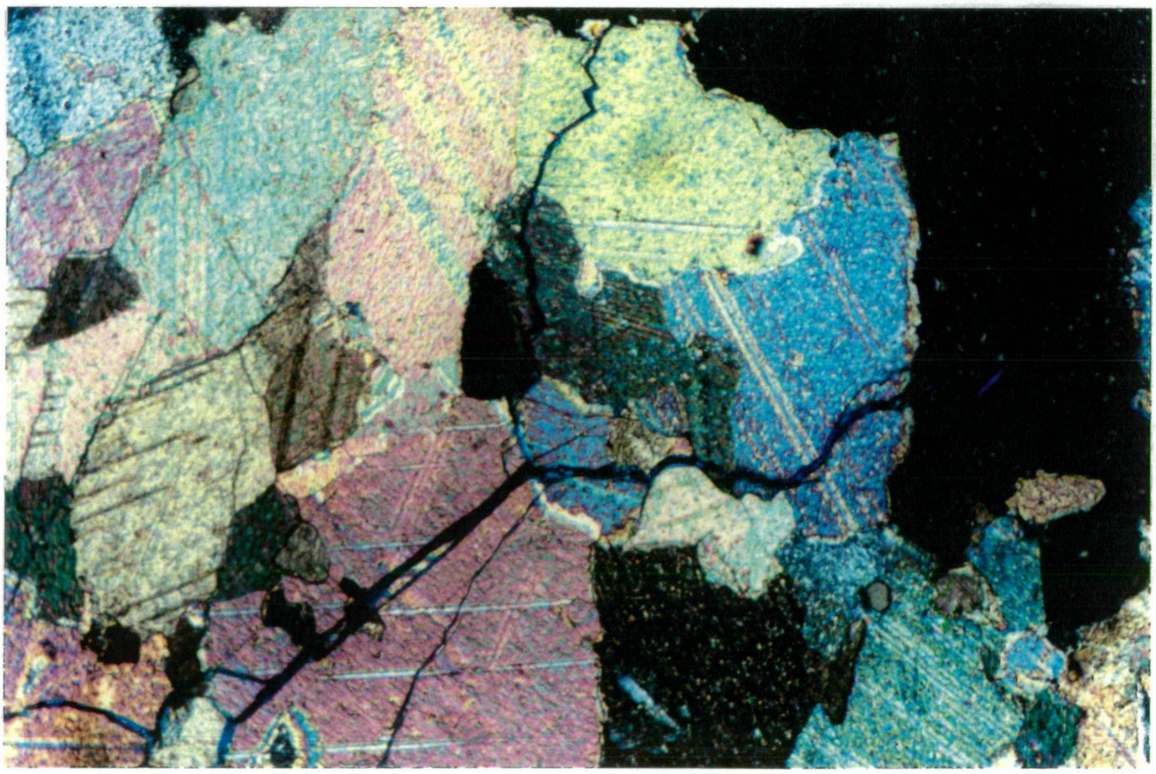
iv. RL360, Eastern Wall, Southern Pit.

360A: Fresh, fine to medium grained, white saccharoidal marble with grains up to 2 mm across (Photomicrograph 10). Grains range in shape from equant to lath-like and often exhibit sutured boundaries. There is no evidence of either intergranular or intragranular fracturing, implying that this sample has been unaffected by blasting. The Point Load Strength Index is high at 8 MPa.

360B: Fresh, medium grained, white saccharoidal marble with grains up to 4 mm across. Grains range in shape from equant to lath-like. Grain boundaries are tight and often exhibit suturing. Minor intragranular fracturing has occurred often as a series of stepped fractures. Intergranular fracturing is rare and has resulted from the diffraction of intragranular fractures at the grain boundaries (Photomicrograph 11). This sample has been partially affected by blasting.



Photomicrograph 10: Fresh, fine to medium grained marble showing no signs of disruption due to blasting. Field of view 5 mm.

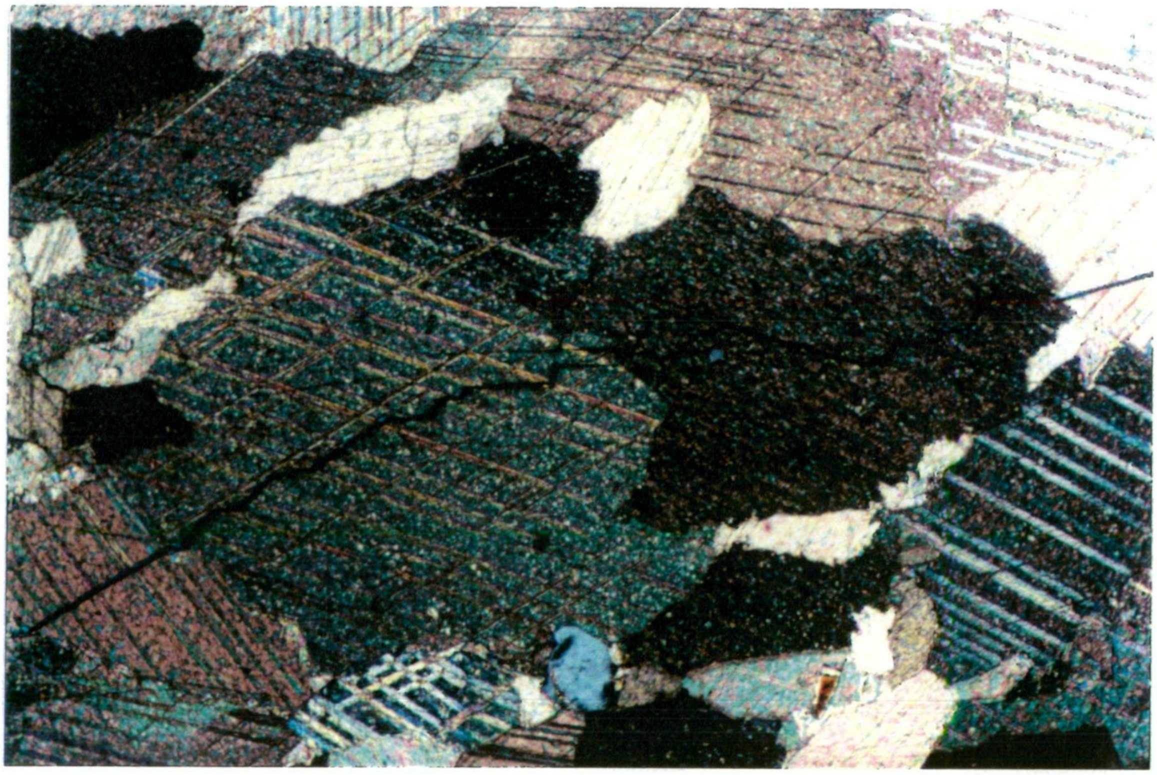


Photomicrograph 11: Fresh, fine to medium grained marble partially affected by blasting. Intragranular fractures are well depicted by the blue dye. Field of view 5 mm.

v. **RL372, Eastern Wall, Southern Pit.**

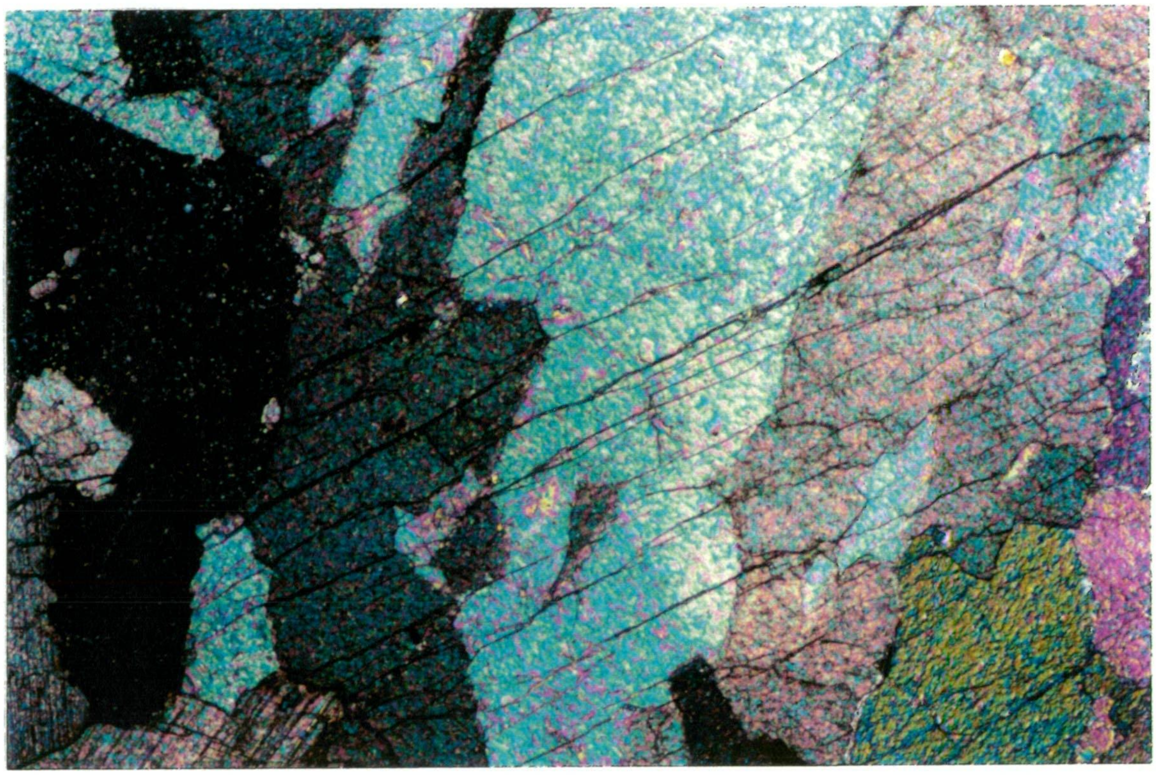
372A: Fresh, medium to coarse grained, white saccharoidal marble with grains up to 5 mm long. Grain boundaries are irregular and sutured and embayments are quite common. Structurally this sample is largely undisturbed with only minor intergranular fracturing having occurred along localised weaknesses. No intragranular fracturing is present. This sample is unaffected by blasting.

372B: Fresh, medium to coarse grained, white saccharoidal marble with grains up to 5 mm long. Grains are generally lath-like with irregular and often sutured boundaries. A distinct mineral lineation is present within localised areas of the sample and not throughout. This may indicate that grain alignment is partially due to the compressive forces produced during blasting. Intergranular fracturing is rare or absent. Minor intragranular fracturing has occurred within some of the larger grains. These fractures tend to be stepped and do not deviate at the grain boundaries (Photomicrograph 12). This sample has been partially affected by blasting. The Point Load Strength Index measured approximately 4 MPa indicating a medium rock strength.



Photomicrograph 12: Fresh, fine to medium grained marble showing distinct stepped intragranular fractures (blue dye). Field of view 5 mm.

372D: Fresh, medium to coarse grained, white saccharoidal marble with grains up to 5 mm long. Grains are generally lath-like with irregular and sometimes sutured boundaries. This sample exhibits intense structural damage both along grain boundaries and within the grains themselves. The fracturing is pervasive with the intragranular fractures dominating over the intergranular fractures. The intragranular fractures do not deviate at the grain boundaries but tend to propagate through multiple grains. Some en-echelon type fracturing also occurs. The dominance of the intragranular fracturing over the intergranular fracturing indicates that the strength of the grain boundaries is greater than that of the grains themselves (Photomicrograph 13). The Point Load Strength Index is around 1 MPa which indicates that the rock strength class is low.



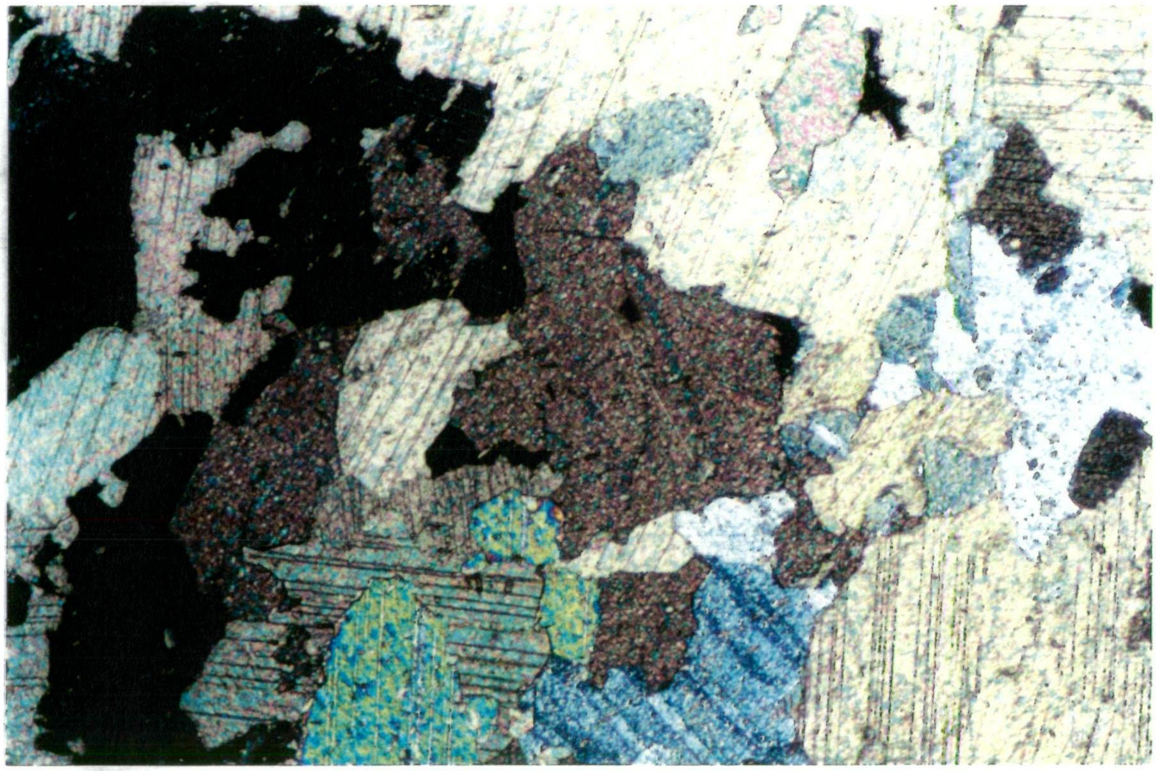
Photomicrograph 13: Fresh, medium to coarse grained marble exhibiting intense fracturing (intragranular) due to blasting. Field of view 5 mm.

vi. RL384, Eastern Wall, Southern Pit.

384A: Fresh, fine to medium grained, white saccharoidal marble with grains up to 3 mm across. Grains range from equant to lath-like with irregular and often sutured grain boundaries

(Photomicrograph 14). No intragranular or intergranular fracturing is evident. This sample has maintained it's structural integrity which is supported by a Point Load Strength Index of around 9 MPa. This sample has been unaffected by blasting.

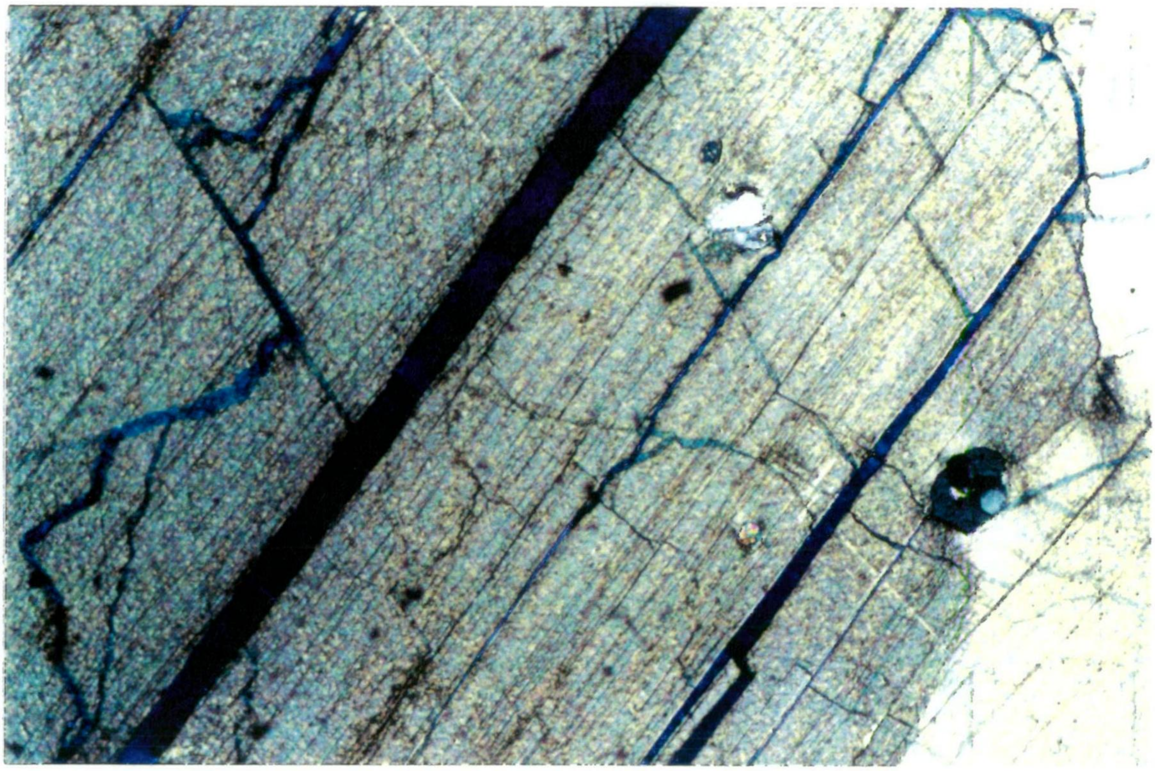
384B: Fresh, coarse grained, white saccharoidal marble with grains up to 9 mm long. Some grains are equant in shape but the majority are lath-like with well cemented, distinct but often irregular grain boundaries. Both intergranular and intragranular fracturing occurs within this sample with the intragranular fracturing dominating. Some of the intragranular fractures exhibit an en-echelon fracture pattern. The intragranular fractures tend to be more prevalent within the larger grains. This sample has been partially blast affected and like many of the coarse grained samples shows that the grain boundary strength is greater than the strength of the grains themselves.



Photomicrograph 14: Fresh, fine to medium grained marble unaffected by blasting. Field of view 5 mm.

384C: Fresh, coarse grained, white saccharoidal marble with grains up to 7 mm long. Grains are largely lath-like with grain boundaries being sharp and regular. Sutured grain boundaries are rare.

Both intergranular and intragranular fractures occur with the intragranular fractures dominating. Some of the intragranular fractures also exhibit a distinct parting (Photomicrograph 15). Many of the intragranular fractures are sub-parallel to the long axis of the mineral grain. As with the other coarse grained samples the larger grains are the most susceptible to blast damage. This sample has been heavily affected by blasting which is supported by a Point Load Strength Index of 1-2 MPa (i.e. a low to medium rock strength classification).



Photomicrograph 15: Fresh, coarse grained marble heavily affected by blasting. The intragranular fracturing is very evident due to the blue dye impregnation. Field of view 5 mm.

4.2.3 ANALYSIS OF PETROGRAPHIC INVESTIGATIONS

The petrographic investigations showed that blast affected marble comprises a combination of intergranular and intragranular fractures. Downstream performance of the marble, that is, its decrepitation potential in the kilns operation is directly related to its fracture density.

The petrography also showed that grain size, grain shape and the grain boundary conditions (i.e. cementing agents and /or suturing) played an important role in the determination of the dominant fracture type. For example, where the marble comprised fine to medium, equidimensional grains with poorly sutured or cemented boundaries, intergranular fractures dominated (e.g. Sample 315D - Photomicrograph 6). Conversely, where the marble comprised coarse, lath-like grains with well sutured or cemented boundaries, intragranular fractures dominated (e.g. Sample 384C - Photomicrograph 15). A combination of grain sizes, grain shapes and boundary conditions often resulted in both fracture types being present.

In addition, despite the Handibulk Wet being identified as a greater producer of blast affected marble, compared to ANFO, both explosive types produced similar fracture patterns under the same petrological conditions (i.e. grain size, grain shape and grain boundary characteristics).

The fractures ranged from tight to open (i.e. up to 0.20 mm across) with both linear and stepped fractures being common (e.g. Sample 384C - Photomicrograph 15 exhibited both stepped and linear fractures). Where present the fractures were generally pervasive (i.e. traversed length of thin section). The degree of variability was high with some samples exhibiting single, isolated fractures (e.g. Sample 372B - Photomicrograph 12) whilst others exhibited a complex system of multiple, closely spaced, often anastomosing fractures (e.g. Sample 303C - Photomicrograph 2).

The petrographic work indicated that the major difference between marginally blast affected marbles (e.g. Sample 303B - Photomicrograph 1) and intensely blast affected marbles (e.g. Sample 303C - Photomicrograph 2) of similar physical characteristics was essentially the number of fractures present (i.e. fracture density) rather than the nature of the fractures. Possibly the only change that did occur in the nature of the fractures with changes in fracture density was the openness of the fractures. Where a single fracture dominated it was often more open than where multiple fracture systems occurred. However, the fracture density and not the openness of the fractures appeared to have the greatest influence on the Point Load Strength Index and therefore the compressive strength of the sample.

Where multiple intragranular fractures occurred they were often sub-parallel to one another and linked via bridging fractures. This was especially common where the intragranular fractures were very closely spaced (e.g. Sample 348D - Photomicrograph 9). A similar phenomena occurred where there were multiple intergranular fractures but instead of the bridging fractures propagating through the grains they occurred at grain boundaries (e.g. Sample 315D - Photomicrograph 7).

The point load tests indicated that the Point Load Strength Index (and therefore the unconfined compressive strengths of the marble) varied both laterally and vertically throughout the pit. The point load tests conducted on the hand specimens were compared to fracture density which was determined by conducting a fracture count on the appropriate thin section. A log-log graph of fractures per centimetre versus the Point Load Strength Index (PSLI) was compiled (Figure 5) which showed a reduction in strength with increased fracture density and also that the marble in the southern end of the pit generally exhibited higher strength values than the marble in the northern end of the pit.

It was not clear if these strength differences were a function of depth or if they were due to lateral variations (particularly north-south) within the deposit. If they were a function of depth then it is likely that we will experience similar levels of blast affected marble in the southern end of the pit as it is developed below the water table and necessitates the use of waterproof explosives. However, if the differences were the result of lateral variations (i.e. north-south) then we may find that the levels of blast affected marble from both wet and dry blasting will be comparatively less in the southern end of the pit than in the northern end given the results shown in Figure 5. It is unlikely that east-west lateral variations were a major factor as the southern pit samples spanned a significant proportion of the cross sectional area of the pit but maintained relatively consistent properties in terms of Point Load Strength versus fracture density.

These findings also support the opening statements to the thesis, where a change in the mining practices to a dominantly northern pit blend was considered to be a major contributor to the recent increases of decrepitating marble in the Osborne kilns.

Point Load Strength Index (PLSI) versus Fractures/cm

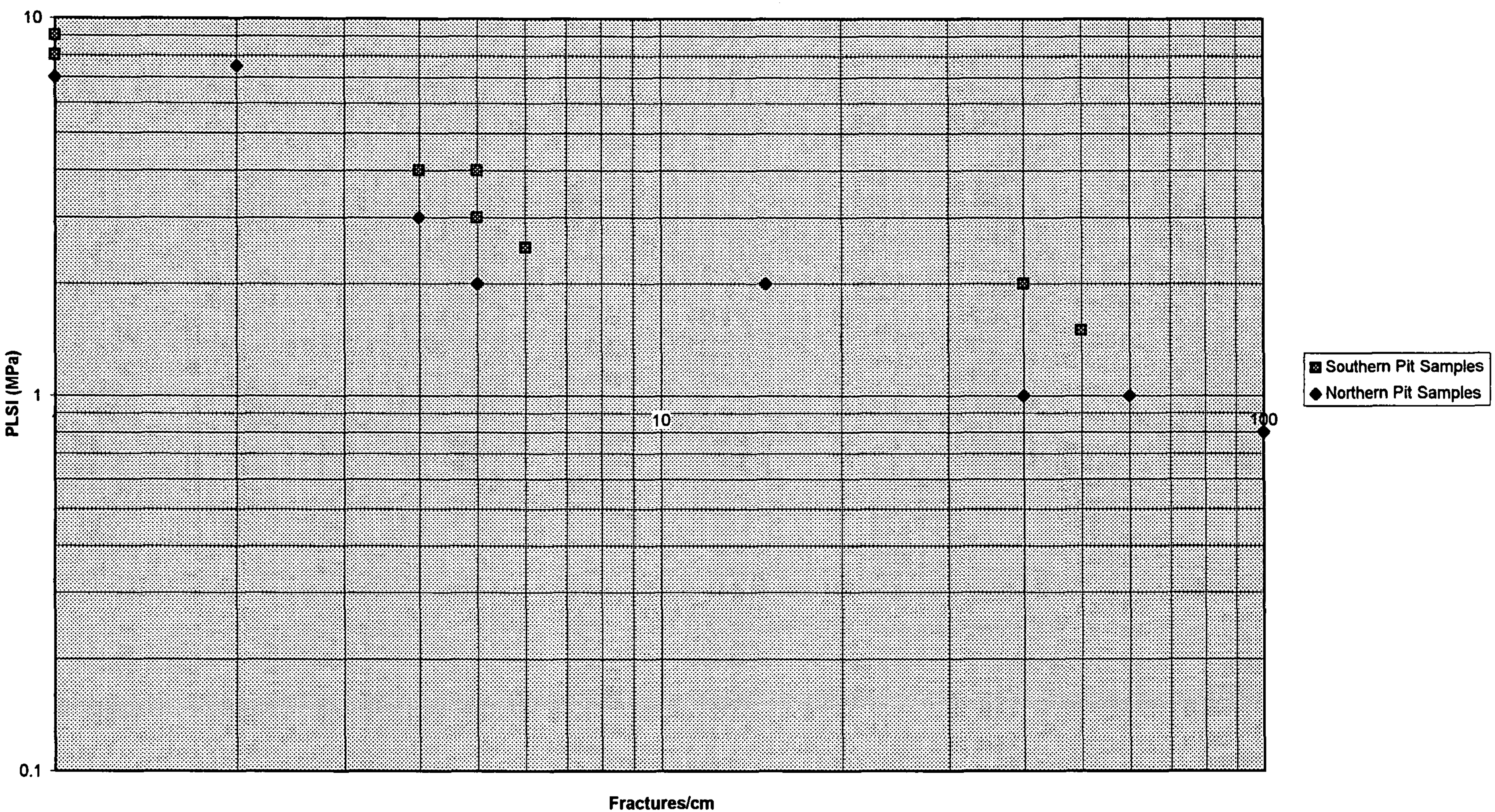


Figure 5: Log-log graph of Point Load Strength Index versus Fractures/cm.

5. CONCLUSIONS

It has been shown that the level of blast affected marble is attributable to at least two major parameters acting concurrently. These are, the physical characteristics of the marble and the characteristics of the explosive type being used. Although only one method of blasting was used for this study it is likely that different blasting practices would contribute to varying amounts of blast affected marble. This feature will be discussed in more detail in part iv. - Blasting Practices.

Since the physical characteristics of the marble (i.e. grain size, grain shape, grain boundaries and compressive strength) are already determined the solution(s) to alleviating blast affected marble lie largely with the explosive type and how it is used. Other avenues, such as mining practice (i.e. production scheduling), will not influence the levels of blast affected marble produced but they may enable it to be directed away from the kiln operation. Each of these topics will be discussed below.

i. MINING PRACTICES

Mining practices play a significant role in that, the downstream effects of processing blast affected marble can be alleviated by scheduling marble of low in-situ compressive strength to customers other than the kilns at Penrice's Osborne operation. This is particularly pertinent in areas of the pit where mining is conducted below the water table necessitating the use of wet hole explosive types, such as Handibulk Wet. Changes to the mining practices (i.e. production scheduling) have been trialled at the Penrice Quarry with varying degrees of success. Unfortunately, the long term implementation of these types of production scheduling changes is limited by the finite reserves and the need to blend marble from as many benches in the pit as practicable. Current work on the long term mine plans will determine if there is any scope in the future for introducing more permanent changes to the mining practices.

ii. PIT DEWATERING

Another avenue that is also being investigated is the aspect of major dewatering operations in the lower benches of the pit to enable Handibulk Wet to be replaced by ANFO. At best this would see the current levels of blast affected marble attributable to Handibulk Wet reduced to those levels encountered with dry hole blasting (i.e. ANFO). To date this approach has met with minimal success as it has necessitated a large scale pumping operation which cannot be economically sustained for the long term. This has been further complicated by the fact that water ingress to the lower levels is rapid once the pumps have been stopped and relocated prior to blasting. This means that any ANFO present in the blast holes would be desensitized if it came into contact with this water. This has very serious safety implications as it could result in a misfire (i.e. incomplete detonation) as well as causing major delays to the production process.

iii. PRODUCT DEVELOPMENT

Numerous discussions have been conducted with ICI Explosives Technical Services and have centred around the potential development of a new explosive type that may be able to replace Handibulk Wet. The fragmentation analysis indicated that both explosive types (i.e. Handibulk Wet and ANFO) did the same amount of work in the rock mass but Handibulk Wet produced much more blast affected marble. These results have shown that the Relative Bulk Energy (RBE) and therefore the Velocity of Detonation (VOD) of the Handibulk Wet is too high for its desired application at the Penrice Quarry. It was suggested that there was a real need for a waterproof explosive (i.e. won't desensitize in water) with a Relative Bulk Energy (RBE) close to that of ANFO (i.e. 100 % as compared to 159 %).

ICI Explosives have spent considerable time and effort to try and determine if it is possible to develop such an explosive type for Penrice's specific needs. ICI Explosives suggested that the development of a brand new explosive type was cost prohibitive but that there may be some scope in the area of mixing currently available explosive types with a range of inert materials. It was suggested that the addition of an inert material (e.g. polystyrene beads) would enable the Relative Bulk Energy to be decreased, but to date ICI Explosives had not overcome the waterproofing issue. The development of an alternative explosive type is likely to take considerable time and would necessitate extensive testing to determine both its suitability and reliability.

At this stage it appears that no short term gains will be made from this area of research, but ICI Explosives and Penrice have committed specific resources to investigating all the developmental possibilities.

iv. BLASTING PRACTICES

Changing or modifying aspects of the current blasting practices appears to offer some scope for reducing the levels of blast affected marble. It was decided that the best approach would be to modify one aspect of the current blasting practices at a time and see what influence each had on the level of blast affected marble.

However, it was decided that one aspect of the current blasting practices, that is, the initiation sequence would remain unmodified as ICI Explosives suggested that the current configuration allowed for optimum burden relief and rock pile throw.

Blast pattern configuration has recently changed from a staggered pattern of 3.6 metres burden by 3.6 metres spacing to a staggered pattern of 3.6 metres burden by 4.2 metres spacing. Although no formal photogrammetric/fragmentation analysis has been conducted at this stage on a blasted rock pile using this configuration some general observations have been made, namely:

a. the volume of oversize material increased placing a greater burden on the level of secondary rock breaking required.

b. the volume of undersize material (i.e. minus 50 mm) decreased thereby increasing the volume of Osborne size stone (i.e. + 50 mm to - 150 mm) in each blast. This appeared to offset the costs associated with increased secondary rock breaking.

c. the new blast pattern configuration has enabled the Penrice Quarry to reduce its explosives use in some areas thereby producing a cost saving to the operation.

d. the levels of blast affected marble did not appear to change, but it should be noted that only basic visual assessments have been conducted at this stage and not a formal fragmentation analysis.

It is hoped to be able to utilise ICI Explosives Technical Services to undertake a fragmentation analysis for some trial blasts using this blast pattern configuration. Despite the visual assessment being inconclusive the kilns operation at Osborne have seen some improvements in kiln pressures, 'grits' generation and temperature profiles which may indicate that the overall levels of blast affected marble have in fact decreased. Until a formal study is completed it has been decided to adopt this new blast pattern configuration as standard practice at the Penrice Quarry.

Another aspect of the current blasting practice that is being investigated is the possibility of undertaking a trial using a decoupled blast. A decoupled blast is one where the diameter of the explosive column within the blasthole is less than the diameter of the blasthole. This is usually expressed as a percentage and is called the decoupling ratio. Current blasting practices at the Penrice Quarry use a decoupling ratio of 100 %, that is, the explosive column is the same diameter as the blasthole. It is known that borehole pressure is quite intense for a blasthole with 100 % decoupling ratio and therefore the decoupling method may be effective in reducing blast damage (i.e. blast affected marble). The decoupling media between the explosive charge and the sides of the blasthole may be either water, air or some form of inert material.

The major logistical problem with decoupled blasts is the centralising of the explosive column in the blasthole so that the decoupling media is consistent along the length of the explosive column. The Penrice Quarry uses bulk explosives rather than packaged explosives which means that setting up a decoupled blasting trial would be very time consuming. The Penrice Quarry Technical Group are investigating the best possible way in which a trial of this nature may be instigated. If this method were to prove successful there would need to be considerable work done in regards to changing the way in which blastholes are currently loaded. This may prove to be too costly in the long term.

Although it was decided not to modify the surface initiation sequences currently practiced, it was suggested by ICI Explosives that modifications to down-hole initiation practices may yield some positive results. The explosive columns within the blastholes are currently initiated from the bottom, largely due to convenience and low cost. With this method the explosive column reaches its maximum

Velocity of Detonation (VOD) because it has had sufficient distance, called run-up distance, to reach full explosive potential. It has been suggested that side initiation may be an alternative down-hole initiation technique. Side initiation involves placing the detonator and primer part way down the explosive column instead of at the base. This means that the run-up distance is significantly reduced and may be low enough to hinder the explosive from reaching its full Velocity of Detonation potential. In essence, the explosive will produce less shock energy but should produce more in the form of heave energy. This means that rock pile throw should be greater without the expense of heavy fragmentation and high levels of blast affected marble.

Any trial using side initiation will need to be very well understood prior to implementation because the Penrice Quarry wishes to keep rock pile throw to a minimum because of its production blending practices. Product contamination is of paramount to the quarry operation and therefore rock pile throw must be minimised. The other consideration is the environmentally sensitive area in which the quarry is situated as side initiation has a tendency to increase the levels of noise and ground vibration.

The final aspect of the current blasting practices that was discussed as an area for possible modification was that of alternative stemming materials. Stemming is the inert substance filled between the explosive column and the collar of the blasthole and is used to confine the explosive gases. Stemming material could be water, sand, drill cuttings, crushed rock or gravel. According to Sen (1995) under the effect of the impulsive gas pressure, dry angular crushed rock tends to form a compaction arch, which locks into the blasthole wall, increasing its resistance to ejection. Sen (1995) suggests that the stemming material should ideally be around one-twelfth of the blasthole diameter. At the Penrice Quarry a 7 mm screened marble is used as this gives good interlocking properties (i.e. equivalent to one-sixteenth of the blasthole diameter of 114 mm) and its chemical composition is such that contamination of high grade marble will not occur.

The current stemming material is performing well as it has contributed to reductions in the incidence of air-blast, fly rock and overbreak problems. At this stage an alternative material has not been put forward for trial but this avenue is still open for revisitation. The only stipulation at this stage is that any alternative stemming material must not result in contamination to the high grade marble and thereby produce quality control problems.

6. SUMMARY

It has become increasingly evident that there are many variables that may contribute to the phenomena of blast affected marble. For this reason a long term solution is likely to take some time to be fully implemented. Although it is likely that ongoing trials will be conducted, foremost in our thinking must be the costs associated with making any permanent changes to our current mining and/or blasting practices.

It is important that during the trial stages we alter only one variable at a time in order that we may gain as complete an understanding as possible on the effect of changing that particular variable. This study has shown that the only way to reduce decrepitation in the kilns is to reduce the levels of blast affected marble and this can only happen by altering the way in which the explosives are able to act upon the marble itself. This is in preference to a change in our mining practices as it is unlikely that scheduling highly blast affected marble to another customer could be sustained long term given our blending requirements and reserve status. The petrographic study also showed that the way in which the explosives alter the rock structure and ultimately its strength characteristics through the development of various fracture systems is an irreversible process that cannot be eliminated only controlled.

BIBLIOGRAPHY

Anon., 1988. EXPLO88 - Explosives in Mining Workshop, 1988. The Australasian Institute of Mining and Metallurgy.

Beevers, John., 1994. Quarry Blasting The Latest Technology. ICI Australia Operations Pty Ltd.

Bluck, R. G., 1985. An Assessment of Stone Grade Within The Penrice Quarry. Report for ICI Australia (unpublished).

Campbell, J. D., 1945. The Geology of the Angaston Marble Beds, South Australia. Report to I.C.I. Alkali (Australia) Pty. Ltd.

Cameron, M. J., 1990. Some Aspects of Environmentally Effective Blasting for Quarries. Proc. Australian Institute of Quarrying Conference - Hobart 1990.

Curtis, J. L.,1990. Penrice Soda Products Pty Ltd Kiln Decrepitation - A Synopsis. JLC Exploration Services (unpublished).

Drexel, J. F., Preiss, W. V. and Parker, A. J., 1993. The Geology of South Australia. Vol. 1, The Precambrian. South Australia Geological Survey. Bulletin, 54.

Drexel, J. F., Preiss, W. V. (Eds), 1995. The Geology of South Australia. Vol. 2, The Phanerozoic. South Australia Geological Survey. Bulletin, 54.

Glascodine, R. D. S., 1973. Report of Discussions During a Tour of Limestone Quarrying and Limeburning Operations in Canada and the U.S.A. ICI Australia Company Report (unpublished).

Graham, A. M., 1996. Geological Mapping of the Penrice Marble Mine, March 1996. Penrice Minerals Group - Technical Services report (unpublished).

Graham, A. M., 1988. Geology of the Henschke Area. South Australian Institute of Technology. B.App.Sc. thesis (unpublished).

ICI Explosives., 1994. Reduction in Blast Affected Marble. A report on the joint technical service project between ICI Explosives and Penrice Soda Products (unpublished - incomplete).

Johnson, P., 1992. Quality Control at Penrice Marble Quarry. Johnson Geological Consultants Pty. Ltd. report to PSP (unpublished).

Kerr, Paul. F., 1977. Optical Mineralogy. McGraw Hill. Fourth Edition.

Lapworth, Mark., 1982. Limestone Decrepitation Tests At Osborne Kilns. ICI Australia Operations Pty Ltd, Osborne (unpublished).

Little, Trevor. N. (Ed), 1994. Open Pit Blasting Workshop 94. Printing Services Curtin University of Technology.

Martin, A. M., 1980. CRL Research - Osborne: Decrepitation Study - Present. ICI Australia - Osborne Report (unpublished).

Sen, Gour. C., 1995. Blasting Technology for Mining and Civil Engineers. University of New south Wales Press Ltd.

Spittle, H. M., 1937. The Examination and Burning of Limestone Samples From Nos. 9, 13, 14 & 19 Boreholes, Angaston Quarry. ICI Australia Company Report (unpublished).

Stapledon, D. H., 1982. Penrice Marble Quarry - Geotechnical Studies Report on Stage 1. Report for ICI Australia (unpublished).

Stapledon, D. H. and Stevens, 1983. Penrice Marble Quarry - Geotechnical Studies - Stage 2. Report for ICI Australia (unpublished).

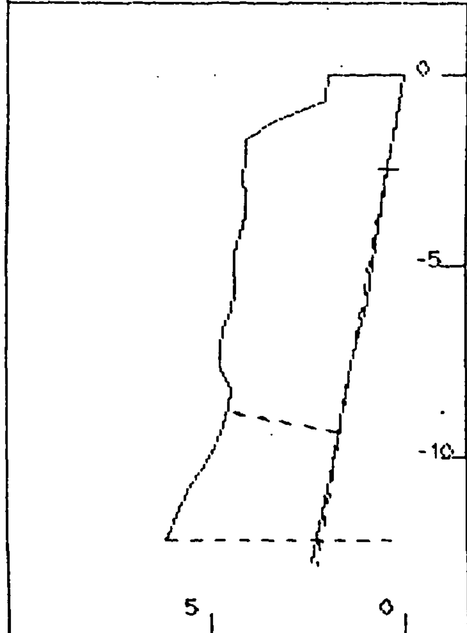
Wagland, D. G., 1984. Geology, slope stability and landscaping of screening mounds at Penrice Quarry. South Australian Institute of Technology Honours thesis (unpublished).

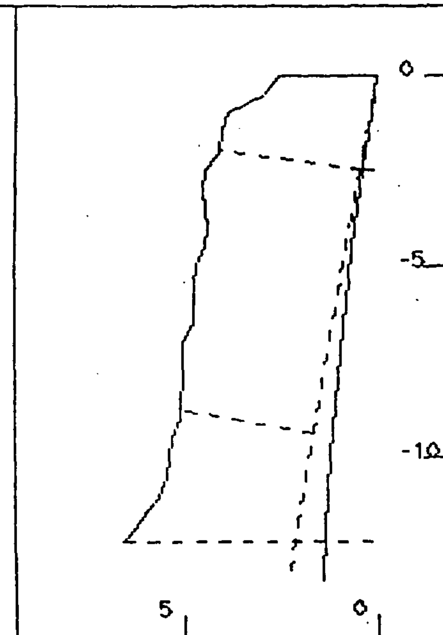
APPENDIX 1

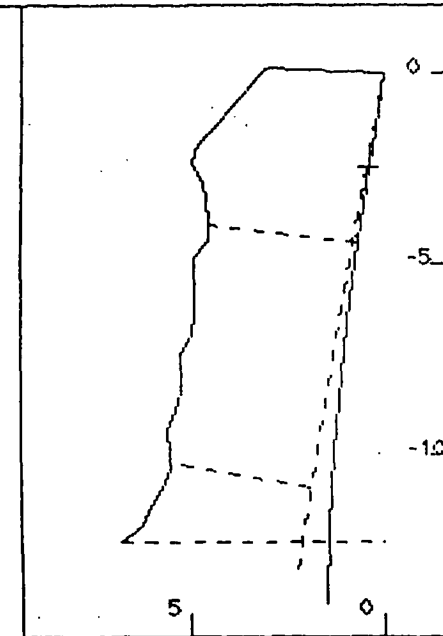
BLASTHOLE SURVEY

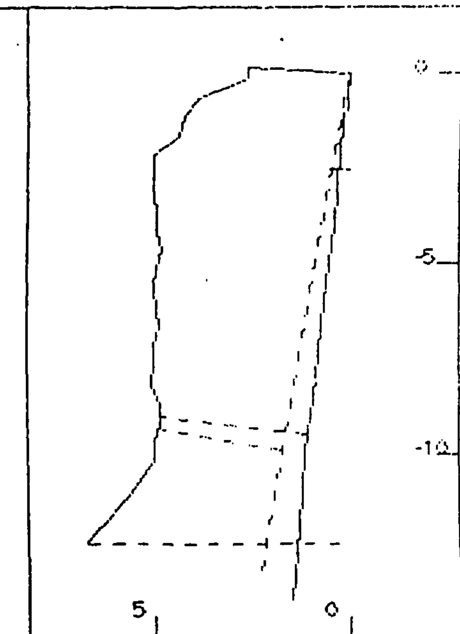
REPORTS

Profile Cross Sections









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OFFSET (m):	1	
DR AGL (deg):	9.9	
H DEPTH (m):	13	(13)
(SDR) (m):	.6	(.6)
MIN BUR (m):	2.9	(2.9)
BUR DTH (m):	9.5	(9.5)
AREA (Sq m):	40	(40)
VOL (Cu m):	154	(154)

PROF 2(Edit.)		(Intended)
BENCH HT (m):	12.2	
ALONG (m):	3.7	
OFFSET (m):	.6	
DR AGL (deg):	9.9	
H DEPTH (m):	13.3	(13.1)
(SDR) (m):	.9	(.7)
MIN BUR (m):	3.7	(3.5)
BUR DTH (m):	2.5	(9.5)
AREA (Sq m):	48	(45)
VOL (Cu m):	184	(171)

PROF 3(Edit.)		(Intended)
BENCH HT (m):	12.4	
ALONG (m):	7.5	
OFFSET (m):	.6	
DR AGL (deg):	9.9	
H DEPTH (m):	14	(13.2)
(SDR) (m):	1.5	(.8)
MIN BUR (m):	3.8	(3.6)
BUR DTH (m):	4.5	(11)
AREA (Sq m):	51	(48)
VOL (Cu m):	196	(184)

PROF 4(Edit.)		(Intended)
BENCH HT (m):	12.4	
ALONG (m):	11.3	
OFFSET (m):	-.4	
DR AGL (deg):	9.9	
H DEPTH (m):	13.8	(13.2)
(SDR) (m):	1.3	(.7)
MIN BUR (m):	3.8	(3.2)
BUR DTH (m):	9.5	(10)
AREA (Sq m):	53	(47)
VOL (Cu m):	201	(182)

CLIENT : QUARRY SERVICES

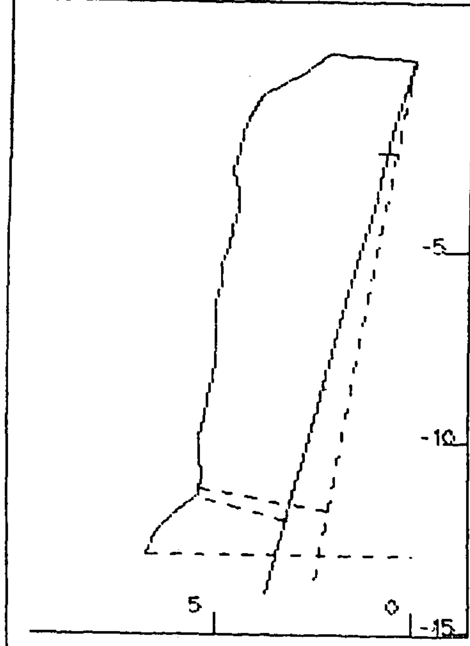
SITE :

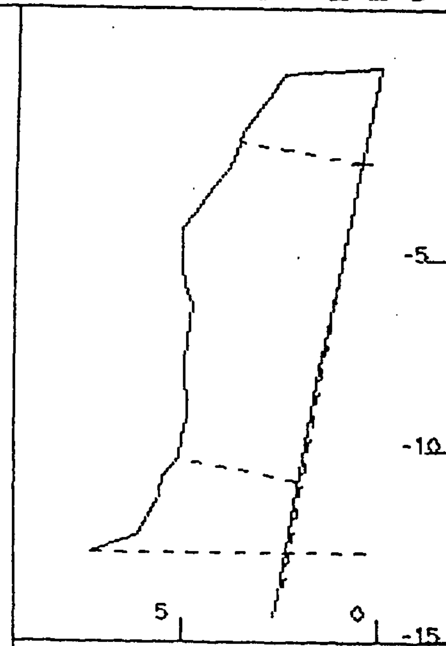
SCALE 1:200
SURVEY DATE :
FILENAME :P1001

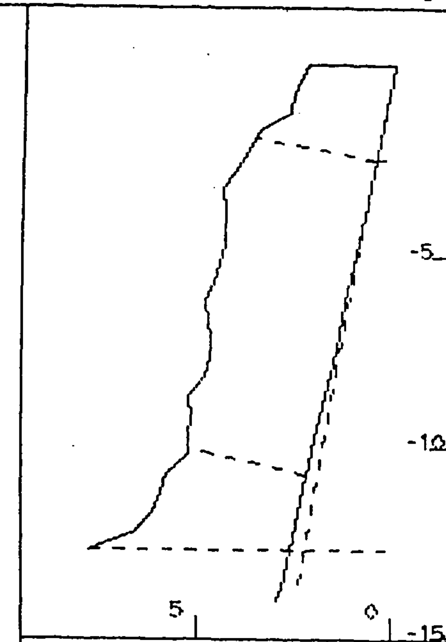
FACE DETAILS

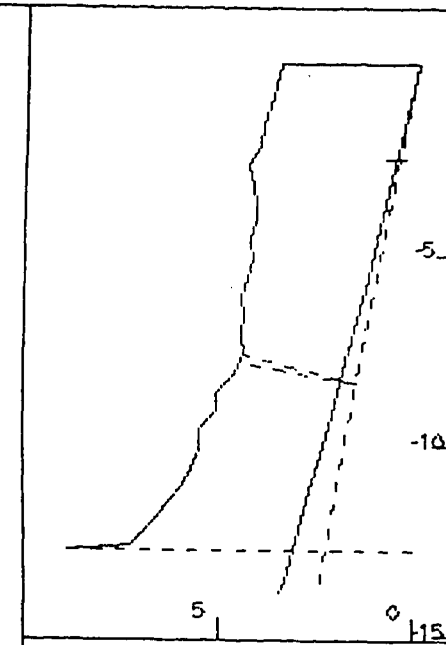
MIN CREST	: 1.9 m
MIN TOE	: 6.1m
MIN BURD	: 2.7 m
TOTAL VOLUME	: 1975 Cu m
TOTAL TONNAGE	: 5235 t
ROCK DENSITY	: 2.65 t/Cu m

Profile Cross Sections









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ALONG (m):	22.7		ALONG (m):	26.6		ALONG (m):	30.3		ALONG (m):	34.2	
OFFSET (m):	.9		OFFSET (m):	.5		OFFSET (m):	.6		OFFSET (m):	1.2	
DR AGL (deg):	9.9		DR AGL (deg):	9.9		DR AGL (deg):	9.9		DR AGL (deg):	9.9	
H DEPTH (m):	14.5	(13.9)	H DEPTH (m):	14.6	(13.7)	H DEPTH (m):	14.3	(13.8)	H DEPTH (m):	14.3	(14)
(SDR) (m):	1.3	(.7)	(SDR) (m):	1.7	(.8)	(SDR) (m):	1.5	(.9)	(SDR) (m):	1.3	(1.1)
MIN BUR (m):	2.3	(3.3)	MIN BUR (m):	3.1	(3.2)	MIN BUR (m):	3	(3.1)	MIN BUR (m):	2.5	(2.9)
BUR DTH (m):	12.5	(12)	BUR DTH (m):	11	(2.5)	BUR DTH (m):	11	(2.5)	BUR DTH (m):	8.5	(8.5)
AREA (Sq m):	41	(48)	AREA (Sq m):	44	(45)	AREA (Sq m):	42	(44)	AREA (Sq m):	41	(45)
VOL (Cu m):	156	(184)	VOL (Cu m):	168	(171)	VOL (Cu m):	162	(169)	VOL (Cu m):	158	(173)

CLIENT : QUARRY SERVICES

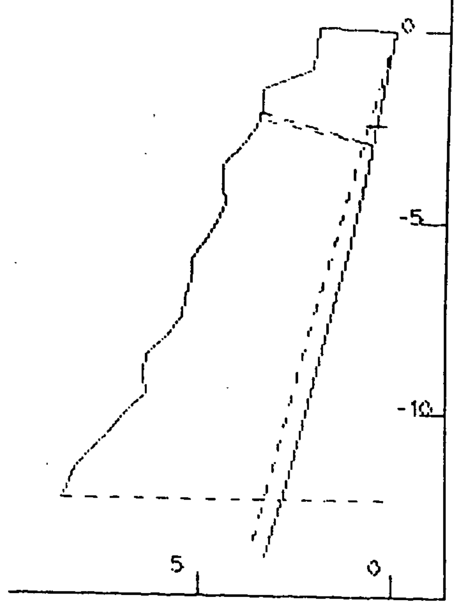
SITE :

SCALE 1:200
SURVEY DATE :
FILENAME :P1001

FACE DETAILS

MIN CREST	: 1.9 m
MIN TOE	: 6.1m
MIN BURD	: 2.3 m
TOTAL VOLUME	: 1938 Cu m
TOTAL TONNAGE	: 5137 t
ROCK DENSITY	: 2.65 t/Cu m

Profile Cross Sections



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(SDR) (m):	1.4	(1.3)
MIN BUR (m):	2.9	(2.7)
BUR DTH (m):	3	(3)
AREA (Sq m):	47	(43)
VOL (Cu m):	179	(163)

CLIENT :QUARRY SERVICES

SITE :

SCALE 1: 200
SURVEY DATE :
FILENAME :P1001

FACE DETAILS

MIN CREST	: 1.9 m
MIN TOE	: 6.1m
MIN BURD	: 2.3 m
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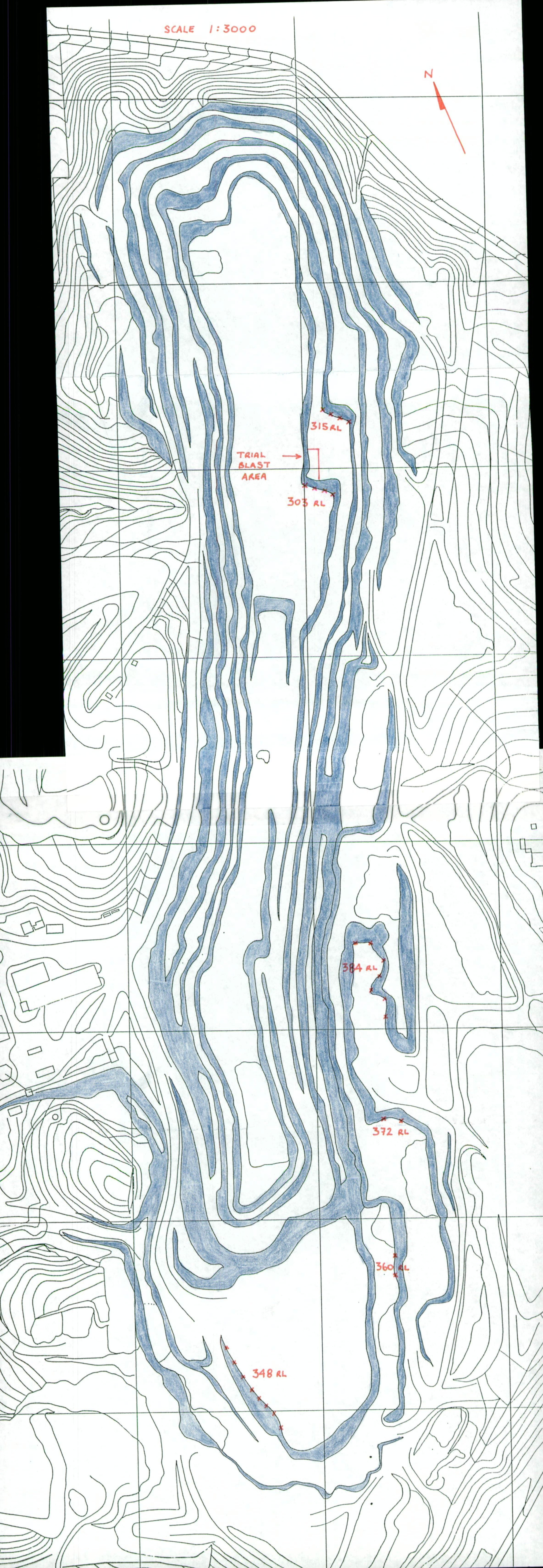
TOTAL TONNAGE	: 5137 t
ROCK DENSITY	: 2.65 t/Cu m

APPENDIX 2

SAMPLE LOCATIONS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BLAST
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